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PIEZOMETRIC MEASUREMENT OF DEPTH
IN OPEN CHANNELS

A THESIS

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the Faculty of the Graduate Division
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IN OPEN CHANNELS

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SUMMARY

Engineering investigations of water flowing in open channels usually require the measurement of flow depth. The most common methods of measurement involve either a direct measurement of the difference in elevation between the water surface and the channel bottom, using a point gage, or measurement of the pressure at a piezometer opening on the walls or floor of the channel, using a manometer.

The object of the present investigation was to compare the results of point-gage and piezometric measurements made under conditions of different channel slopes, Froude numbers, depths, and surface waves. Twenty tests were made, covering a range of channel slopes from 0.00291 to 0.0349, Froude numbers from 0.70 to 3.50, and depths from 0.084 to 0.173 foot. The surface waves were of low amplitude and frequency.

For normal flow conditions (with turbulence, surface waves, and velocity distribution normal for the test flume), the results of the investigation indicated that piezometric measurements of depth gave values greater than corresponding point-gage measurements. The difference between piezometric and point-gage measurements, expressed as a non-dimensional ratio with respect to the depth, was shown to be a function of the piezometric orifice diameter and the Froude number. More significantly, the difference between piezometric and point-gage measurements, expressed as a non-dimensional ratio with respect to the mean velocity head, was shown to be a function of the piezometric orifice diameter only.

In flows with artificial waves (waves generated mechanically upstream from the piezometer test section), depth determinations by point-gage measurements appeared to be dependent upon the wave shape. However, the effect of wave shape on point-gage measurements was not studied. Within the range of the surface waves investigated, the results of the investigation indicated that piezometric measurements of depth were not influenced by these waves.

CHAPTER I

INTRODUCTION

Description of the problem.--In the laboratory study of open-channel flow, one of the primary measurements is that of depth. By depth is meant the distance from the floor of the channel to the mean water-surface elevation. Depth measurements are often obtained by means of a piezometer. A piezometer is essentially a hole carefully drilled into the channel wall or floor. The piezometric head (pressure head plus elevation) is then indicated by a manometer. When the channel floor datum is known, the depth may be easily computed as the piezometric head above the channel floor. In this thesis, the term "piezometric head" is used to designate the piezometrically determined depth.

An alternative method of determining depth is by use of a point gage mounted above the channel. The depth of flow is the difference between the point-gage readings at the water-surface elevation and the channel floor. In the presence of surface waves, precise point-gage measurements can be obtained only with difficulty. Details of methods of obtaining the water-surface elevation in flows with surface waves will be discussed later.

In recent laboratory open-channel research, discrepancies appeared between the depths computed from piezometric observations and those obtained from point-gage observations. These discrepancies in depth measurements represented a significant percentage of the mean flow depth. It was this discrepancy between depth measurements which motivated this investigation.

Scope of the investigation.--The main objective of this investigation was to determine experimentally the factors which influence piezometric observations, and a comparison of the results with direct water-surface measurements. A limited range of flow conditions was investigated. These conditions may be found in Table 1 (page 3).

Review of the literature.--Previous research on piezometer investigations pertained principally to closed conduit flow. The only publication involving open-channel flow, which was known to the writer, was an early paper by H. F. Mills (1). The experiments by Mills compared the piezometric level in external gage wells with that of the free water surface in a wooden channel, thirty feet in length, one foot deep, and four inches in width. About 20 piezometer openings of various sizes and shapes were cut into the walls of the channel. The range of velocities was from 0.5 to 9 feet per second. The piezometer diameters ranged from 0.25 to 1.00 inch. As a result of his experiments with piezometers in the plane of the wall and aligned at right-angles to the wall, Mills concluded that the level of the water column shown by the piezometer read higher than the surface of the water in the channel by an amount equal to $0.000035\ V^2$. For piezometers in the plane of the wall but with connecting passages inclined at an angle to the wall, and for piezometers not in the plane of the wall, Mills reported that the piezometric readings were increased if the inclination was faced upstream and were decreased if the inclination was

Table 1. Summary of Tests

Test No.	Depth D (Ft)	Discharge q (Cu Ft/Ft)	Velocity V (Ft/Sec)	Froude No. F ($V/\sqrt{gD}$)	Slope S_o (Ft/Ft)	Temp. T (^oF)	Remarks
1	0.0890	0.421	4.73	2.80	0.0262	81	(1)
2	0.0870	0.420	4.83	2.86	0.0262	81	(1)
3	0.0840	0.207	2.46	1.50	0.00873	79	(1)
4	0.0845	0.202	2.39	1.45	0.00873	79	(1)
5	0.0895	0.115	1.28	0.75	0.00291	77	(1)
6	0.0880	0.108	1.23	0.73	0.00291	77	(1)
7	0.1730	0.317	1.83	0.77	0.00291	78	(1)
8	0.1720	0.314	1.82	0.76	0.00291	78	(1)
9	0.1725	0.313	1.82	0.77	0.00291	78	(1)
10	0.1420	0.515	3.63	1.69	0.00873	78	(1)
11	0.1420	0.493	3.47	1.62	0.00873	78	(1)
12	0.1485	1.027	6.90	3.16	0.0262	77	(1)
13	0.1485	1.005	6.77	3.10	0.0262	77	(1)
14	0.1410	1.050	7.45	3.50	0.0349	77	(1)
15	0.1240	0.580	4.68	2.35	0.0174	77	(1)
16	0.0880	0.108	1.23	0.73	0.00291	77	(1), (2)
17	0.0880	0.108	1.23	0.73	0.00291	77	(1), (3)
18	0.0855	0.099	1.16	0.70	0.00291	78	(4)
19	0.0905	0.123	1.36	0.80	0.00291	76	(4)
20	0.0915	0.230	2.52	1.47	0.00873	76	(4)

(1) Piezometer traverse.
(2) With mechanically generated surface waves at frequency equal 1.69 cycles per second.
(3) With mechanically generated surface waves at frequency equal 0.90 cycles per second.
(4) Constant diameter opening (piezometer no. 11) only.

faced downstream. For projections faced upstream, large positive errors were recorded. Normal projections or projections faced downstream gave rise to large negative errors. No variation or trend with diameter was observed. Freeman's (2) discussion of Mills' investigation contained the interesting comment:

> The principal cause for possible errors in measurement of comparative heights lay in the "wrinkles" in the surface of the water in the open conduit when flowing at high velocities. Notwithstanding the care taken to maintain a constant level at the entrance of the flume, this surface at higher velocities became somewhat "wrinkled" along its course by small diagonal standing waves.

Research publications of piezometer investigations in closed conduits are more numerous. Publications which were available to the writer were by Allen and Hooper (3), Myadzu (4), Rayle (5), Ray (6), and Shaw (7).

Allen and Hooper experimented with a 12-inch diameter pipe with water flowing at velocities of 4 and 7.2 feet per second. The piezometer openings were drilled in 3/8-inch brass plugs which were threaded into the pipe and scraped flush with the wall. Allen and Hooper reported that the piezometric error was not a function of the piezometer size. The holes varied from 0.063 to 0.688 inch in diameter. Other conclusions drawn from their experiments were: (a) the piezometer error was a constant percentage of the local velocity head at the opening, (b) the piezometer length should be at least twice the piezometer diameter before its shape is changed, (c) a small radius of rounding at the piezometer entrance will not affect the pressure measurement, (d) a large radius of rounding gave a pressure increase up to two per cent of the mean velocity head, and (e) the largest observed errors resulted from misalignments, projections, and burrs.

Myadzu investigated a square conduit with water flowing at velocities up to 14 feet per second. Piezometer diameters ranged from 0.004 to 0.157 inch. Readings were compared with reference piezometers to give a relative error. Absolute errors were obtained by extrapolation. The errors were reported to be positive, increasing linearly with hole diameter, and independent of velocity. It was also reported that the error was independent of the piezometer length-diameter ratio, ℓ/d, provided the ratios were greater than two. The piezometer length is the distance to which the opening extends before its shape is changed.

Rayle conducted experiments both with air at velocities from 400 to 900 feet per second and with water at velocities from 22 to 31 feet per second. Piezometer diameters ranged from 0.006 to 0.125 inch. He reported positive errors which increased with increasing hole diameters and Mach numbers. Geometric modifications of the piezometer opening were also significant. A radius of rounding increased the positive error while a countersink decreased the error.

Ray experimented with a rectangular conduit with a sugar solution flowing at velocities from 0.65 to 12 feet per second. Piezometer diameters varied from 0.039 to 0.394 inch. The results of his investigation indicated a positive error which increased with higher Reynolds numbers and smaller length-diameter ratios. With a very small length-diameter ratio and an enlargement chamber behind the opening, negative pressures were recorded.

Shaw employed a 2-inch diameter pipe with air flowing at velocities from 38 to 212 feet per second. His test section had piezometer openings ranging from 0.016 to 0.189 inch in diameter. All piezometer openings were square-edged. Shaw reported that the pressure error was positive and increased with increasing piezometer hole diameters and increasing flow velocities. For length-diameter ratios greater than 1.5, a single curve expressed the error as a function of a Reynolds number. For smaller values of the length-diameter ratio there was a progressive reduction in the error. In all instances the error was zero at low Reynolds numbers, increased rapidly up to a Reynolds number of about 300, and then progressed less rapidly up to a Reynolds number of about 800, the limit of the investigation. Shaw also demonstrated the effects of drill burrs. He concluded that for a 1/16-inch diameter hole with a length-diameter ratio of four, a burr height of 0.0005 inch produced an error approximately equal to the error due to hole size, and a burr height of 0.0020 inch produced an error approximately equal to seven times the error due to hole size.

Inconsistencies in the results of the various studies are quite apparent and a few remarks are believed pertinent. In Mr. Mills[9] investigation (1878), evidence was presented to emphasize that a high degree of accuracy in methods and measurements was attempted. Today, his equipment and methods might seem crude and inadequate. It appears possible that a wooden flume, with the accompanying warping and swelling of the wood, resulted in errors exceeding those caused by hole size and geometry. In addition, it was stated that surface wrinkles (waves) became a principal cause for possible error. Since Mills compared his piezometric readings with the actual water-surface elevations of the stream, his measurements were limited by the accuracy with which the water-surface elevations could be determined.

Referring to the experiments in enclosed conduits, the apparent contradictions might have been eliminated if the investigators had used the same experimental procedure and analysis. Various authors used different pressure error parameters, means of graphical extrapolation, and testing equipment and procedure, which may have contributed in a large measure to the inconsistencies.

Writer's analysis.--A large scale, cut-away model of a piezometer tap was installed in a glass-walled laboratory flume. Dye was injected into flows corresponding to those reported in this thesis, and the flow behavior was studied by visual observation of the dye streaks. A typical flow pattern at the piezometer tap is shown in Figure 1. (All figures are included in the Appendix.) At the upstream edge of the piezometer, flow separation takes place and results in a displacement of the streamline. The passing liquid entrains some of the fluid at rest in the piezometer opening and generates secondary motion. The downstream edge of the opening tends to block the flow and creates a pitot effect. The combination of the streamline displacement, the eddy motion, and the pitot effect results in a deviation in the piezometric-head indication. Preliminary studies indicated that the piezometric deviation tended toward zero as either the flow velocity or the piezometer hole diameter approaches zero. Conversely, the piezometric deviation or error approached a large value as the hole diameter became large. For a constant piezometer hole diameter, successively higher velocities yielded correspondingly larger piezometric errors.

Functional relationships of the piezometric error with depth of flow, velocity, and hole size remained to be established by the laboratory study.

In the presentation of the results, descriptive parameters were limited to those commonly encountered in open-channel hydraulics. It is hoped that the results of this study may be useful to other open-channel research, and may be applicable to engineering problems.

CHAPTER II

LABORATORY EQUIPMENT

General arrangement.--All tests for the writer's investigation were made in the Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology. The piezometer test section was located in a permanent laboratory flume. Water was supplied to the flume in a six-inch pipe line from the laboratory's constant-head system. A gate valve was used to regulate the discharge. The general arrangement of the equipment is shown in Figure 2.

The flume.--The flume used in this investigation was of adjustable width and adjustable slope. For this study, the channel width was ten inches. The flume was 18 inches deep and 22 feet long from the channel entrance to the tailgate. Water discharged from the supply line through a diffuser and into the flume forebay. Straightening vanes directed the flow from the forebay into the test channel. An adjustable sluice gate near the channel entrance and a sliding tailgate provided controls for uniform flow.

The piezometer test section.--The piezometer test section was located at the downstream end of the flume. The floor slab of the test section was made from 12 gage (0.109 inch) stainless steel plate. The floor of the approach section of the flume was made of brass plate. The floor was smooth and plane. Considerable care was taken to insure a smooth transition between the approach flume and the test section. The walls for both the approach flume and the test section were of 3/8-inch aluminum plate, carefully aligned and clamped to the floor plates.

The piezometer openings were carefully drilled into the floor of the test section. Only the smallest piezometer opening was drilled into a brass plug. The brass plug was tapped into and finished flush with the stainless steel floor plate. A total of 24 piezometers were arranged in groups of three at eight transverse sections. At each section, there were one test piezometer and two reference piezometers. From center to center the piezometers were 0.1 foot apart. The test piezometer was one of the outer piezometers and its position was alternated from section to section. The piezometer sections were 0.2 foot apart. The last piezometer section was located 1.85 feet from the tailgate. This distance was considered sufficiently long to avoid any influence due to tailgate or brink conditions. The test piezometer diameters ranged from 0.031 to 0.375 inch and increased in the downstream direction. All reference piezometer diameters were 0.0595 inch.

For all piezometers the length-diameter ratio was kept constant. A value of length-diameter equal to three was maintained by drilling the proper piezometer length into brass blocks attached to the underside of the test section. Copper tubing connected each of the piezometer taps to a dial-type manifold from which any one piezometer could be connected to several recording devices. All leads were of equal length to avoid a relative influence of tubing length.

Table 2. Summary of Piezometer Openings

Piezometer Number	Piezometer Section	Piezometer Diameter (Inches)	Remarks
1	1	0.0310	(1), (2)
2	1	0.0595	(3)
3	1	0.0595	(4)
4	2	0.0595	(2)
5	2	0.0595	(3)
6	2	0.0595	(4)
7	3	0.0935	(2)
8	3	0.0595	(3)
9	3	0.0595	(4)
10	4	0.1200	(2)
11	4	0.0595	(3)
12	4	0.0595	(4)
13	5	0.1562	(2)
14	5	0.0595	(3)
15	5	0.0595	(4)
16	6	0.1850	(2)
17	6	0.0595	(3)
18	6	0.0595	(4)
19	7	0.2500	(2)
20	7	0.0595	(3)
21	7	0.0595	(4)
22	8	0.3750	(2)
23	8	0.0595	(3)
24	8	0.0595	(4)

(1) Drilled into brass plug.
(2) Test piezometer.
(3) Centerline reference piezometer.
(4) Outer reference piezometer.

Figure 3 shows a plan of the piezometer test section; Figure 4 shows typical construction details at a piezometer section; and Figure 5 illustrates the piezometer connections to the manifold. A summary of the piezometer openings is given in Table 2 (page 11).

Discharge measurements.--Discharges below 0.5 cubic feet per second were measured gravimetrically, using the tank and scales shown in Figure 2. For discharges greater than 0.5 cubic feet per second, a bend meter in the six-inch supply line was used. The accuracy of discharge measurement was believed to be sufficient for the investigation.

The wave generator.--Surface waves were mechanically generated by means of a paddle mounted eccentrically on a rotating wheel. The eccentricity of the paddle was adjustable. Thus, amplitude of the waves could be controlled. The wave frequency was controlled by regulating the air supply to the torque converter which drove the rotating wheel. Maximum frequency was about 2.5 waves per second. The wave generator is illustrated in Figure 6.

Piezometric-head measurements.--The piezometric head at any of the piezometers in the test section could be measured by any one of or a combination of three methods. Two constant displacement-type manometers were permanently mounted to the flume support and had a constant datum regardless of the flume slope. The manometer wells were respectively 0.175 and 1.725 inches in diameter. The advantages of the small-well manometer were its ability to register fluctuations in the piezometric level and to have quick response characteristics. The large-well manometer gave only a time-average reading. A wetting agent (specific gravity equal to 1.000) was used in the smaller manometer to control the capillary rise and to insure a good meniscus. Observations indicated that the amount of wetting agent controlled the height of the capillary rise. Thus, for each test, care was taken to add the same amount of wetting agent.

Both manometers had needles approaching the meniscus from the bottom and both were back-lighted for better observations. When viewing the meniscus from the bottom side, readings were taken at the point where the needle just touched its reflection in the meniscus.

Both manometers were connected with equal lengths of 1/4-inch rubber tubing to petcock valves and then with equal lengths of 1/4-inch copper tubing to the manifold.

The manometer datums were established by means of a known depth of still water in the flume at a zero slope. The channel floor elevation was established and gage zeroes corresponded to this elevation. Depth measurements were thus read directly on the manometer. For flume slopes other than zero, the floor elevation at each piezometer section was computed and used in depth determinations.

In the third method of recording piezometric heads, a differential-type pressure transducer was used in conjunction with a direct-writing recorder. The transducer had a maximum pressure differential of ± 0.15 pounds per square inch.

Attempts to mount the transducer on the flume close to the test section resulted in unsatisfactory performance. The transducer sensitivity was such that mechanical vibrations of the flume created signals which were difficult to evaluate. Consequently, the transducer was mounted on a concrete column some 12 feet from the piezometer test section. Installation included an adjustable staff to keep the pressure-sensing element approximately at the water-surface elevation in the flume. The connection to the transducer was made with 1/4-inch copper tubing and included a petcock valve in the line. It was observed that an open manometer in the system resulted in a dampening of transducer signals. Observations also indicated that even slight movements of rubber tubing were reflected in the transducer readings. Thus, with the line to the transducer open and the valves to the manometers closed, no rubber tubing was in the system leading to the transducer. The valves to the manometers were kept closed during all transducer readings.

The transducer was calibrated for various attenuations of the recorder. The calibration was linear for all attenuations. Thus, for a horizontal channel slope, and a zero reading on the recorder, deviations from the zero reading were computed directly from the oscillographs. For flume slopes other than zero, compensations were made for the deviations from the zero which resulted from changes in flume floor elevations at each section.

In all three methods of depth determinations, facilities for bleeding of the connections and backflushing of the piezometers were included in the system. Considerable care was taken to insure freedom from entrapped air and impurities in the connections. The connections from the manifold are shown in Figure 5 (b). Figure 7 illustrates the manometers. In Figure 2 (b) the transducer is shown mounted on the column. The recorder is in the foreground.

Water-surface measurements.--To obtain results distinguished from the piezometric methods described previously, other water-surface measurements were made. Two devices were used to determine the water-surface elevation.

First, an electric point gage was used. The average water-surface elevation was taken as the midpoint between top and bottom of the fluctuating water surface. Extreme indications of water-surface fluctuations were ignored.

A second method of determining the water-surface elevation used a capacitance-type gage. The device utilized a partially submerged probe which responded instantaneously to the water-surface fluctuations. When connected to one channel of the recorder, the capacitance gage recorded the water-surface profile at a point. The other channel of the two-channel recorder permitted simultaneous transducer measurements.

The capacitance gage had two drawbacks. However, neither was believed to have affected the results appreciably. First, the calibration was not linear with depth. With each successively deeper immersion, the additional corresponding deflection became less. The most nearly linear section of the calibration curve was chosen as the operating range of the capacitance gage.

The second drawback was due to a ride-up of water on the probe, especially at the higher velocities. This influence was eliminated by calibrating the gage in flowing water under the same conditions for which the tests were to be run. An absolute measurement for depths of flow could not be obtained, and a relative measurement was used. The calibration tests were performed by immersing the probe to successively increasing depths and recording the deflection for each depth.

The electric point gage is illustrated in Figure 8 (a). The capacitance gage may be seen in Figure 8 (b). Typical simultaneous transducer recordings of piezometric head and capacitance gage recordings of water-surface fluctuation are reproduced in Figure 9.

CHAPTER III

EXPERIMENTAL PROCEDURE AND ANALYSIS

Scope of the tests.--Twenty tests provided data for the study of the influence of piezometer hole diameter, manometer well diameter, and surface waves on piezometric depth determinations.

Pertinent information for each of the test conditions is shown in Table 1. Tests 1 through 15 provided data to study primarily the influence of piezometer hole size. Tests 16 and 17 (identical in method to tests 1 through 15) had in addition mechanically generated surface waves superposed upon the normal flow. In tests 18 through 20, a single piezometer opening was used to study the influence of surface waves on piezometric measurements.

Influence of size of piezometer opening.--Typical procedure for each test involved flushing of all piezometer connections, calibrating the capacitance gage, balancing the transducer, and establishing uniform flow. Uniform flow was established by regulating the water-surface profile through proper setting of the tailgate or the sluice gate. The water-surface elevations throughout the approach channel were indicated by seven piezometers connected to a multiple manometer board. A sliding hairline on the manometer board indicated uniform flow depth for each slope and discharge; the gate setting was adjusted accordingly.

The discharge, slope, and water temperature were recorded for each test. For each condition of slope and discharge, measurements from each of the 24 piezometer openings were taken with the small-well manometer, large-well manometer, transducer, and capacitance gage. At each of the eight piezometer sections, point-gage readings were taken over the centerline reference piezometer.

From each manometer observation a computed channel floor elevation was subtracted to give the depth of flow. The mean normal-flow depth, D_m, was determined by averaging the depths from the 18 reference piezometers. Both the small-well and the large-well manometers were used in this process. This mean depth was then subtracted from all manometer readings and the results expressed as deviations, $D - D_m$, from the mean normal-flow depth.

On the transducer oscillographs, a straight line was visually fitted to each record to represent the piezometric head. The transducer calibration was used for the conversion into depth measurements. The mean normal-flow depth was obtained again by the averaging of values from the reference piezometers. The differences between the depth at each opening and the mean normal-flow depth were represented as deviations, $D - D_m$.

To study the influence of piezometer hole diameter, the depth obtained from the centerline piezometer was subtracted from the depth obtained from the adjacent test piezometer. The resulting difference, $D_t - D_r$, represented the relative influence of piezometer diameter. The use of adjacent piezometers eliminated the possible effects of slight non-uniform flow conditions. The outer reference piezometers were not used except to indicate extremes of depth in the water-surface profiles. Only in tests 7 through 9 were such transverse variations in depth observed. In these tests the Froude number was close to one, and the depth was larger than the other depths of flow investigated. A characteristic of the flow in tests 7 through 9 was a "wash-board" water surface.

Influence of surface waves.--Tests 18 through 20 were run to determine the influence of surface waves on piezometric observations. In these tests, a single piezometer (piezometer number 11) was used. Waves of variable but known frequency were set into motion by the wave generator. Between runs with mechanically generated surface waves, a basis of comparison was provided by runs with normal flow conditions. Measurements included simultaneous recordings by the transducer and the capacitance gage. For some of the runs, measurements were also taken with the large-well and small-well manometers.

These tests were made at one depth and two Froude numbers. One Froude number was in the supercritical flow range and the other in the subcritical flow range. For each test, three amplitudes of waves were generated. The wave generator acted as an oscillating sluice gate and the water-surface elevations were varied by the sluicing effect. Transducer and capacitance-gage readings, taken simultaneously and at the same test section, were used to study the influence of surface waves on piezometric measurements.

The surface waves extended the full width of the channel and had steep fronts and gradually decaying backs. Because of the asymmetric wave shape, a mean depth determination was attempted by equating the volumes in the wave crests and in the wave troughs. This determination was difficult because of the non-linearity of the capacitance gage. With the aid of the calibration curve, a line was determined to represent the mean depth. This depth was compared with the corresponding value from the transducer record.

CHAPTER IV

DISCUSSION OF RESULTS

Simultaneous piezometric-head and water-surface recordings.--Figure 9 illustrates enlarged typical recordings of the water surface (capacitance gage) and piezometric head (transducer) for normal flow conditions. The water-surface recording shown was corrected for the nonlinearity of the capacitance gage. A time lag of about 0.1 second existed between the two records. This lag was due to the length of tubing connecting the piezometer to the transducer.

The recordings in Figure 9 indicated that the normal flow was characterized by swells of a low frequency, one to two per second, and low amplitude, about 0.003 foot in height. Random capillary waves occurred in all flows and are reflected in Figure 9 (a). The average amplitude of the capillary waves was from 0.001 to 0.002 foot. The capillary waves did not create a response in the transducer record (see Figure 9 (b)).

Influence of size of piezometer opening.--The results of tests to determine the influence of piezometer size on piezometric measurements are shown in Figures 10 through 24 (tests 1 through 15). Part (a) of each of these figures illustrates the agreement among the eight centerline piezometric readings and among the three different methods of measurement.

As described earlier, the deviation or error was expressed relative to reference piezometers of 0.0595 inch diameter. Part (b) of Figures 10 through 24 shows the relative error, $D_t - D_r$, as a function of the size of piezometer opening. The error curves revealed that the error was not only a function of the piezometer hole diameter, but was also a function of the depth of flow and the velocity.

The effect of depth was eliminated by dividing the relative error by the mean normal-flow depth, D_m. The results were expressed as a percentage of the depth. This dimensionless parameter, $(D_t - D_r)/D_m$, was plotted as a function of the piezometer hole diameter in Part (c) of Figures 10 through 24. A summary of the Part (c) curves for these tests is shown in Figure 25 (a). There, the relative error is shown to be also a function of the Froude number.

Since it was assumed that there would be no error at a zero diameter hole, the curves were redrawn to correspond to zero error at a zero diameter. Errors based on the zero-diameter extrapolation are designated as "absolute errors". Figure 25 (b) was obtained from Figure 25 (a) by a vertical translation of the curves and extrapolation to a zero diameter. For an alternative presentation, Figure 26 was prepared from Figure 25 (b). This plot further illustrates the interrelationship between the variables. With all variables except the mean normal-flow depth remaining constant, it was evident from Figures 25 and 26 that the piezometric error may be expressed as a percentage of the depth. For each Froude number, a separate curve difined the error as a function of piezometer hole diameter.

Many closed-conduit experiments have indicated that the piezometric error was proportional to the dynamic head. Division of the relative error of Part (b) of Figures 10 through 24 by the mean velocity head for each test yielded the curves shown in Part (d) of the same figures. A single curve fitted the data. The single curve which described the absolute error as a percentage of the mean velocity head is shown in Figure 27. This curve shows comprehensively the piezometric error as a function of the piezometer hole diameter.

The scatter of the points in Figures 10 through 24 was in evidence during the tests. At the outset of the study, all piezometer holes were carefully inspected for freedom from burrs and trapped impurities. In addition, the piezometers were thoroughly backflushed before each test. In spite of this care, it was observed during the testing program that some piezometers were partially obstructed. The influence of a slight clogging was evidenced by the lowered values for these piezometers. Following the discovery of the partially clogged holes, a general refurbishing of the test section was undertaken. This resulted, however, in the distortion of another opening. The experience served to illustrate that slight imperfections in the construction and maintenance of the piezometers were almost inevitable and may have been responsible for the scatter of the data.

The point scatter in Part (d) can be explained as follows. In tests with low velocities, the velocity heads were small and exaggerated the scatter. For example, the mean velocity head in test 5 (Figure 14) was 0.024 foot. A reading error of only 0.0005 foot in the measurement of piezometric head, when expressed as a percentage of the mean velocity head, would have amounted to a value of over two per cent. The test data at higher velocities showed better agreement. To further refine the results, the curves for Parts (b) and (c) of Figures 10 through 24 were made consistent with the single curve of Part (d). The curve shown in Part (d) was obtained by using data from all tests, but with particular reliance on data from tests at higher velocities. The agreement between the refined curves and the plotted data was very satisfactory.

Figures 10 through 24 also served for a study of the influences of manometer well diameter and method of measurement. Within the range of observation, no systematic trend due to manometer well diameter was observed. The transducer measurements coincided with or differed only slightly from the manometer readings.

Comparison of piezometric and point-gage measurements.--Preliminary comparisons of point-gage depths and piezometric-heads indicated that the point-gage depths were lower than the piezometrically determined depths. This was due to the inherent positive error in the piezometric measurements. The piezometrically established depths were corrected by use of the relationships shown in Figures 25 through 27. Figures 25 and 26 relate the absolute error to Froude numbers and piezometer hole size. Figure 27 shows the absolute error as a function of piezometer diameter only. An actual piezometric observation must be corrected by the appropriate absolute error in order to yield the mean normal-flow depth. This mean normal-flow depth was in very close agreement with the mean normal-flow depth established by point-gage measurements.

The difficulty of obtaining the mean normal-flow depth by the method of point-gage measurements was related to the amplitude of the water-surface fluctuations. The amplitude and the rapidity of the fluctuations increased with Froude number. Transducer records were used to study these fluctuations. Figure 28 shows the piezometric-head fluctuations as functions of Froude number and piezometer hole size. For piezometer hole diameters in excess of 0.25 inch, the piezometric-head fluctuation became independent of the hole size and was only a function of the Froude number. Figure 28 may also serve as an index of the difficulty with which reliable point-gage measurements could be made.

Influence of surface waves.--Results of tests to determine the influence of mechanically generated surface waves on piezometric measurements are presented in Figures 29 and 30. These tests were made with one piezometer only. Figure 29 illustrates various wave heights of the mechanically generated surface waves in relation to wave frequency. Figure 30 shows data of the mean normal-flow depths obtained from continuous records of the capacitance-gage and the transducer. The results from the two methods are consistent. Although not shown, the mean normal-flow depth obtained from manometer readings coincided with the data on Figure 30.

Figure 30 indicated that mechanically generated surface waves did not influence piezometric measurements in tests 19 and 20. Additional information was obtained from the results of tests 16 and 17. In these tests the effects of surface waves were studied for all piezometer sizes. Data of tests 16 and 17 were compared with data of tests 5 and 6 which had nearly identical conditions of slope, discharge, and depth. No influence due to surface waves was discernible between the two sets of data.

CHAPTER V

CONCLUSIONS

Twenty tests, including approximately 3000 observations, comprised the study of the influence of flow conditions and piezometer size on depth determinations in open-channel flows. The range of tests conditions included channel slopes from 0.00291 to 0.0349, Froude numbers from 0.70 to 3.50, depths from 0.084 to 0.173 foot, and piezometer diameters from 0.031 to 0.375 inch.

The effect of piezometer size was to create a positive piezometric-head error which increased with a larger piezometer diameter, depth of flow, and Froude number. For a constant Froude number, the error was expressed as a percentage of the depth and a function of the piezometer hole diameter. For all flow conditions, the error was expressed as a percentage of the mean velocity head and a function of the piezometer hole diameter. In general, the absolute error (zero error at zero hole diameter) increased rapidly up to the point where the diameter was about 0.07 inch, and then increased less rapidly. The error reached an almost constant positive value at large piezometer diameters.

Some tests with mechanically generated surface waves indicated that piezometric measurements were not influenced by surface waves. Mean piezometric readings, corrected for the positive error due to size of piezometer opening, corresponded to mean water-surface elevations. This phase of the study amplified the difficulty in obtaining point-gage measurements and indicated that the validity of point-gage measurements depended upon the wave shape.

The study showed that piezometric observations, when corrected in accordance with Figures 25 through 27, provided an accurate determination of depth for open-channel flow. Except for extreme conditions of the water surface, the study indicated that a skilled observer could obtain point-gage readings that concurred with corrected piezometric readings.

Throughout the tests, all piezometer holes were maintained nearly perfect in construction details. Hence, the test results apply only to square-edged piezometer openings aligned normal to the floor. The length-diameter ratio of the piezometers was constant. The flow depths for all tests were shallow, and the walls and floor of the flume were smooth.

The effects of larger flow depths, variations in piezometer geometry, and wall roughness deserve attention in future research.

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APPENDIX

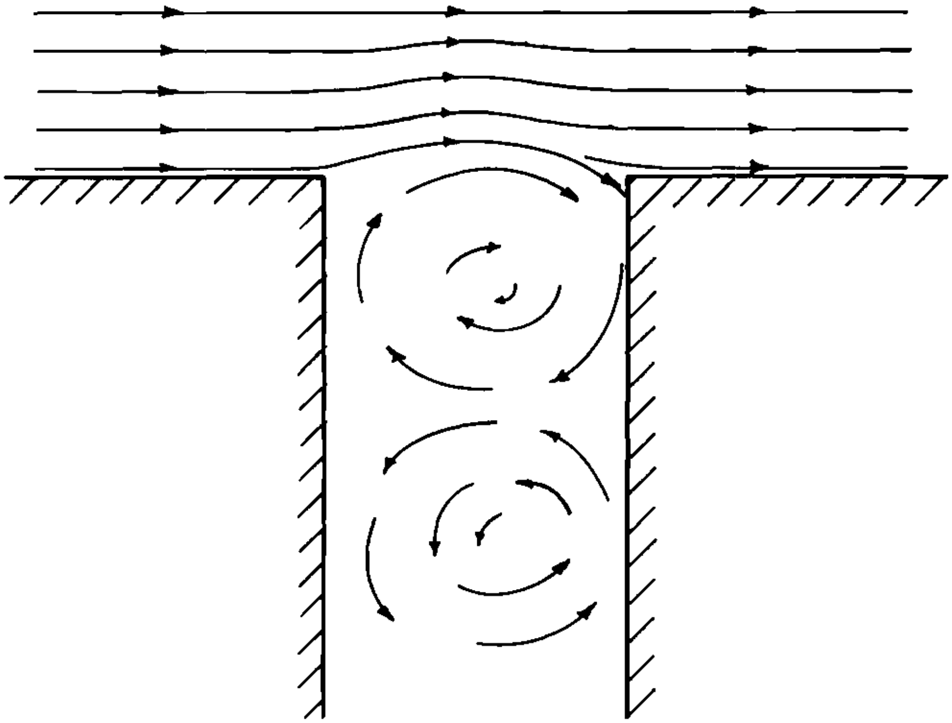
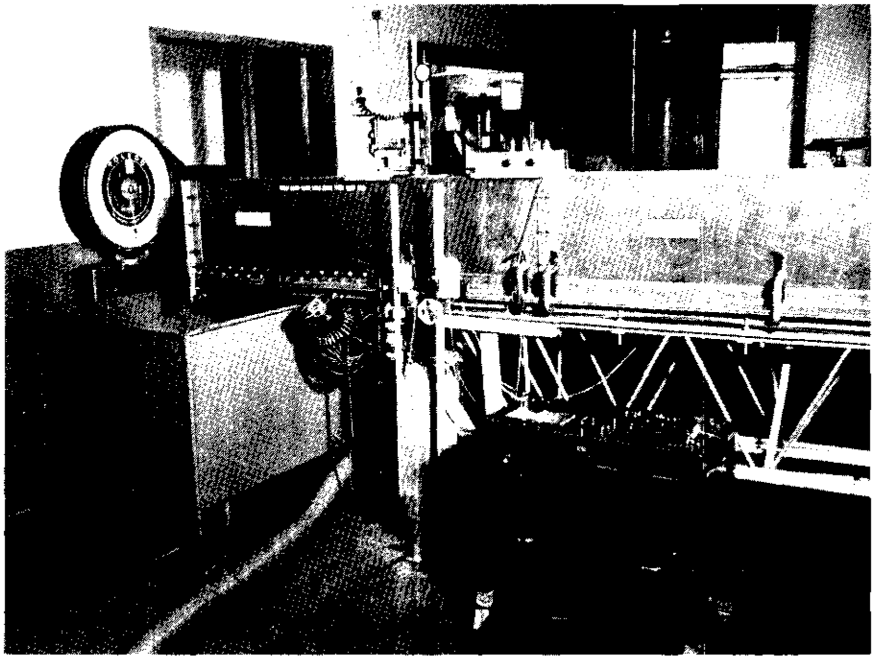
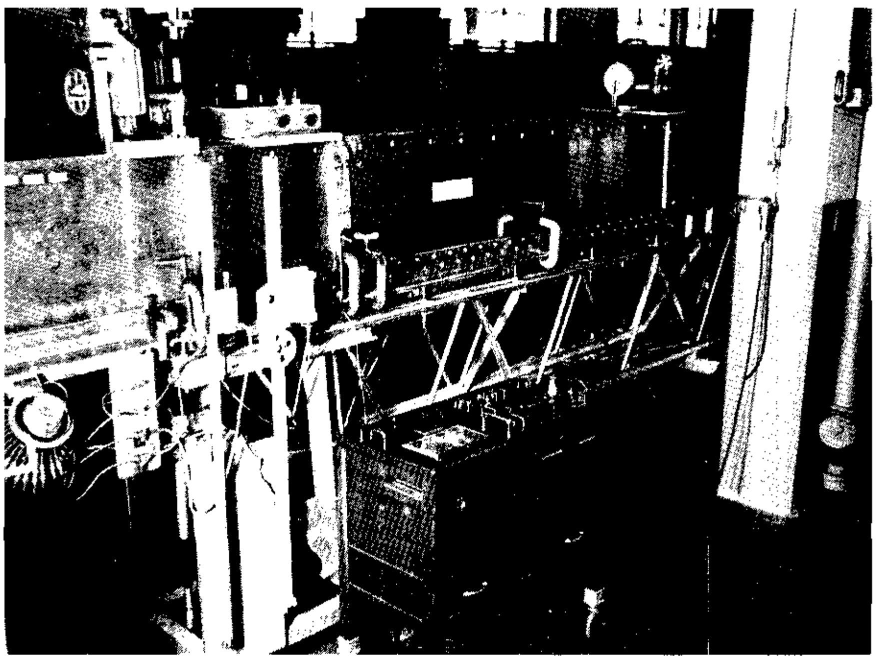


Figure 1. Typical Flow Pattern at a Piezometer.



(a) Looking Downstream



(b) Looking Upstream

Figure 2. Arrangement of Experimental Apparatus.

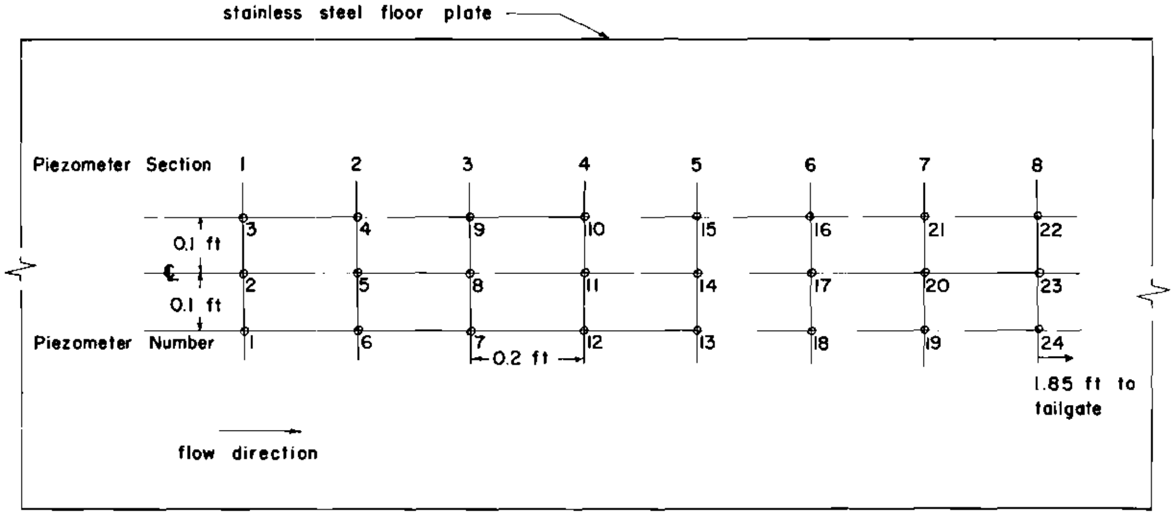


Figure 3. Plan View of Piezometer Test Section.

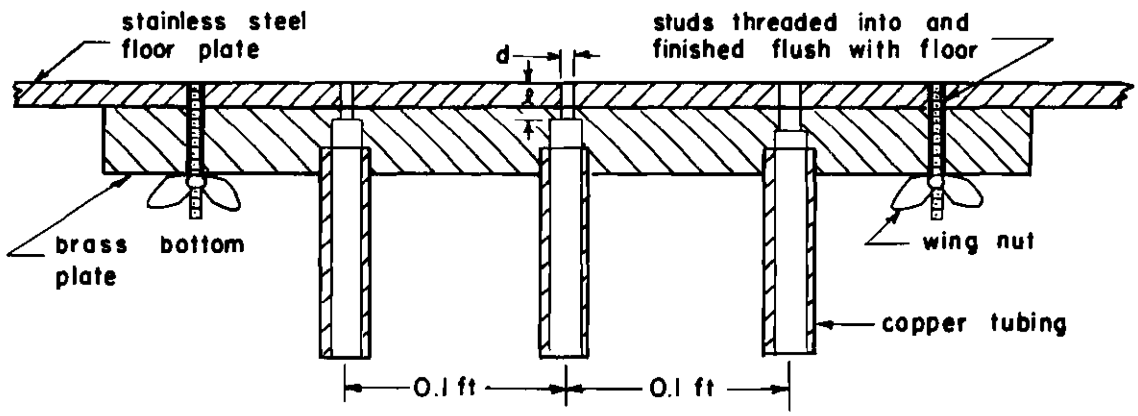
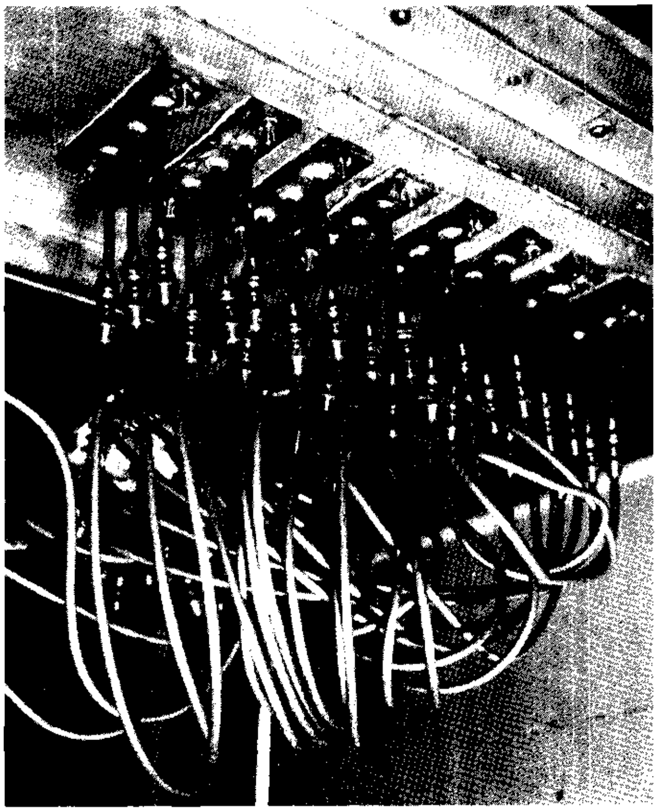
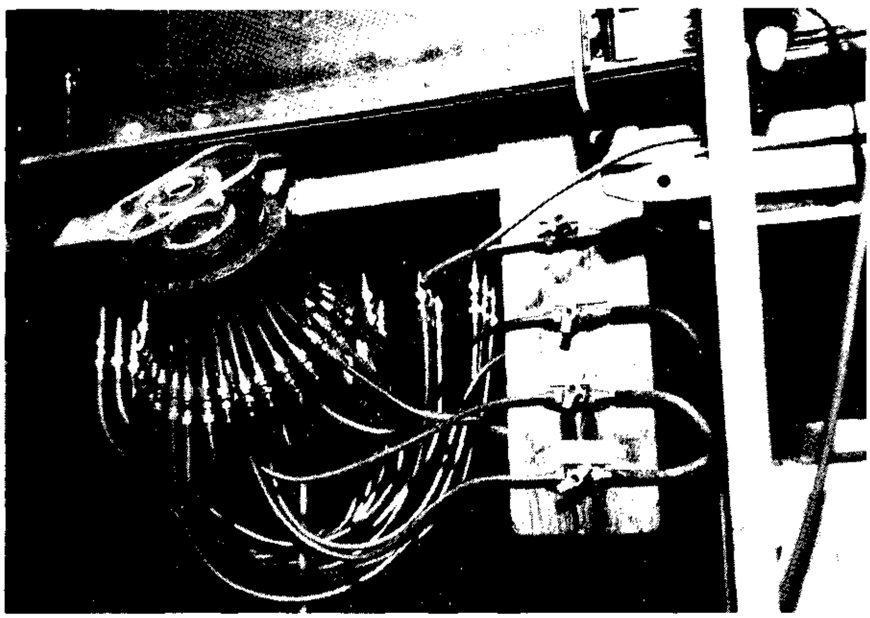


Figure 4. Typical Cross-section of Piezometer Openings.



(a) Bottom View of Test Section



(b) Dial-Type Manifold

Figure 5. Piezometer Connections.

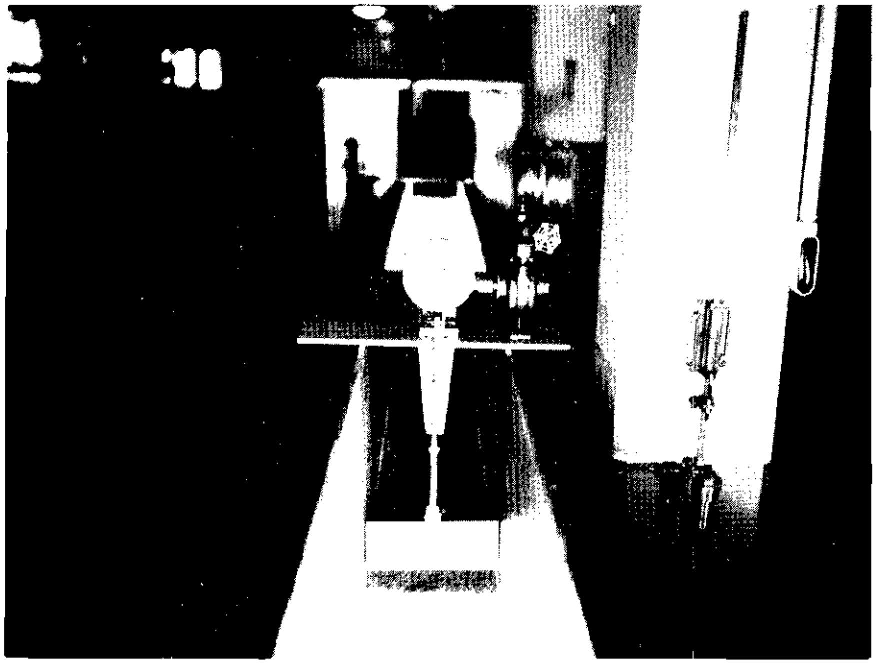


Figure 6. Wave Generator.

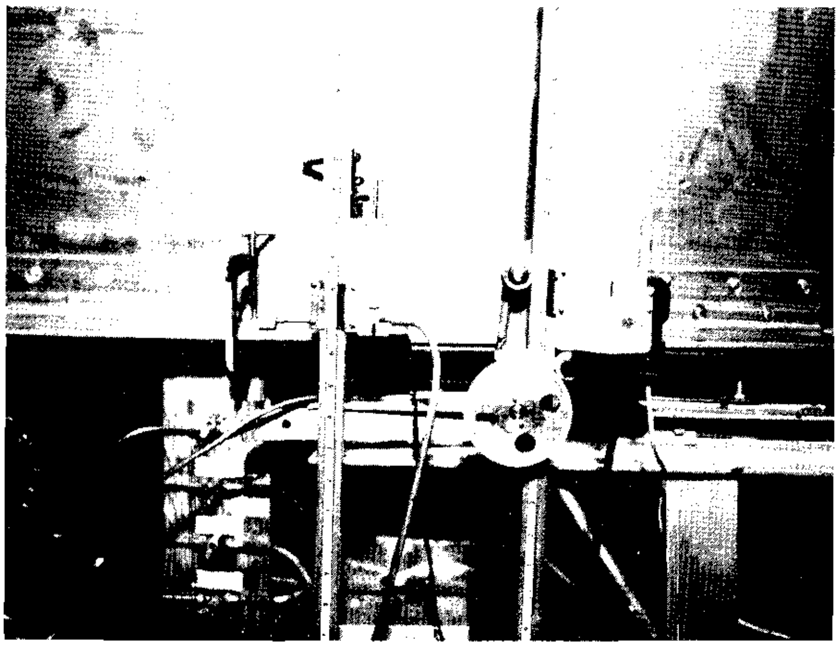
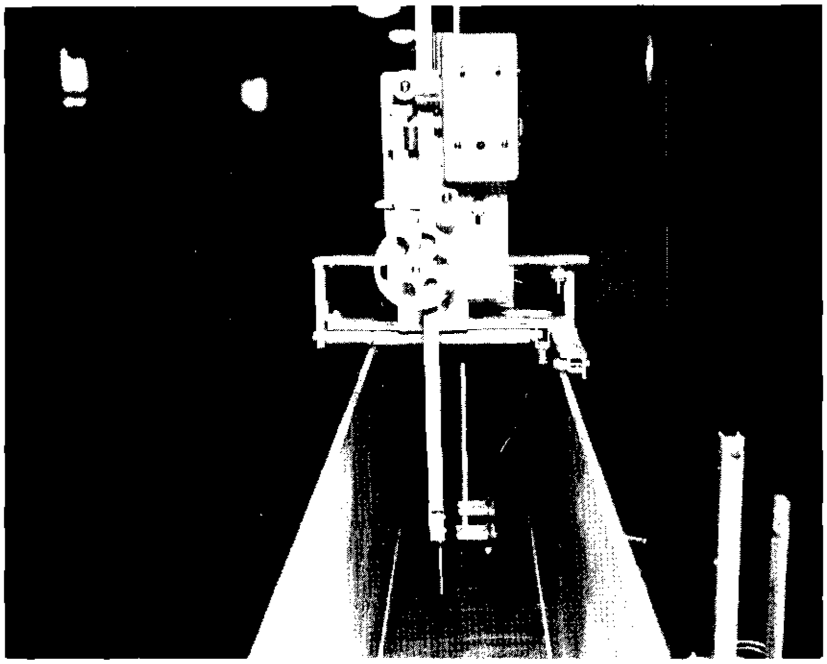
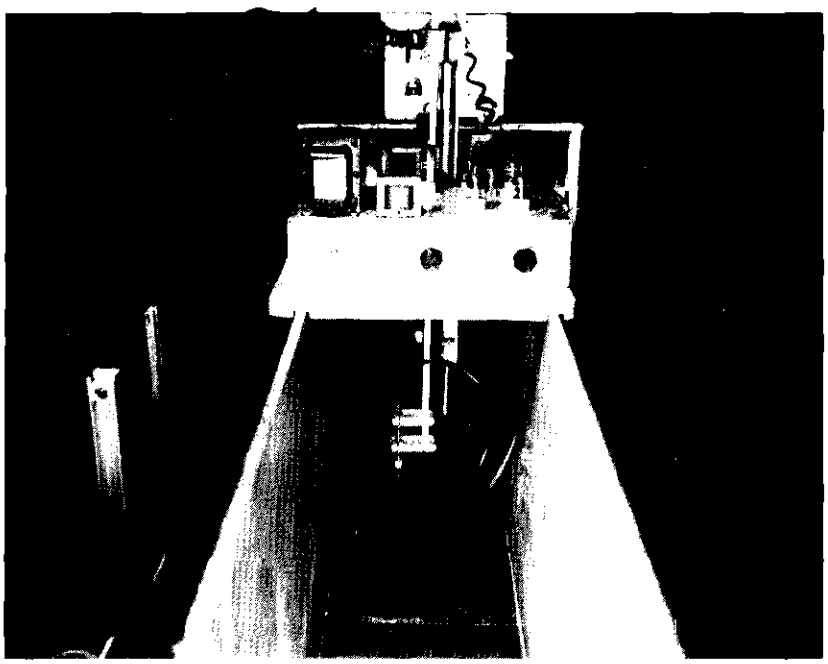


Figure 7. Manometers Used for Piezometric Measurements.



(a) Point Gage



(b) Capacitance Gage

Figure 8. Apparatus for Water-Surface Measurements.

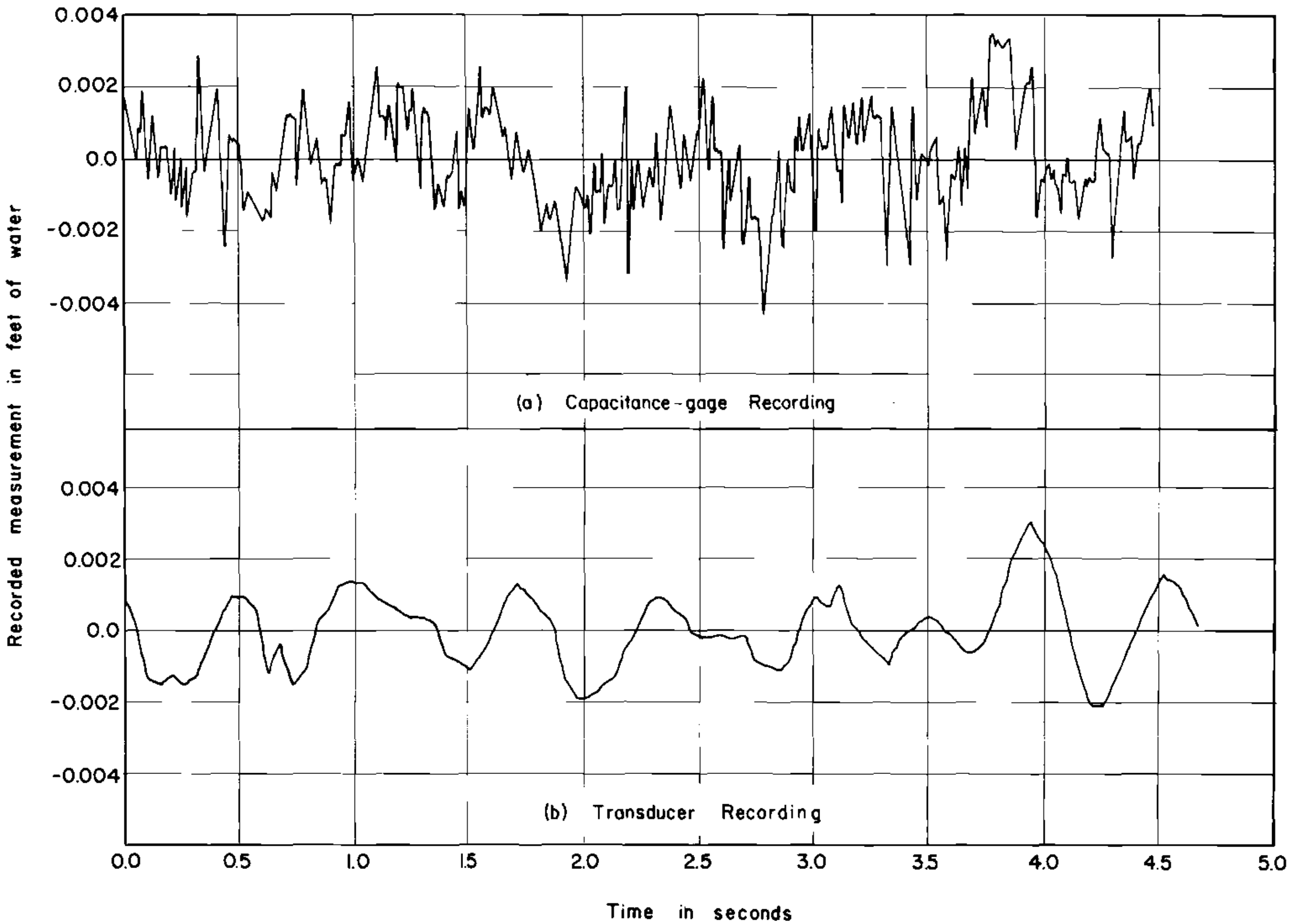


Figure 9. Typical Simultaneous Water-Surface and Piezometric-Head Recording.

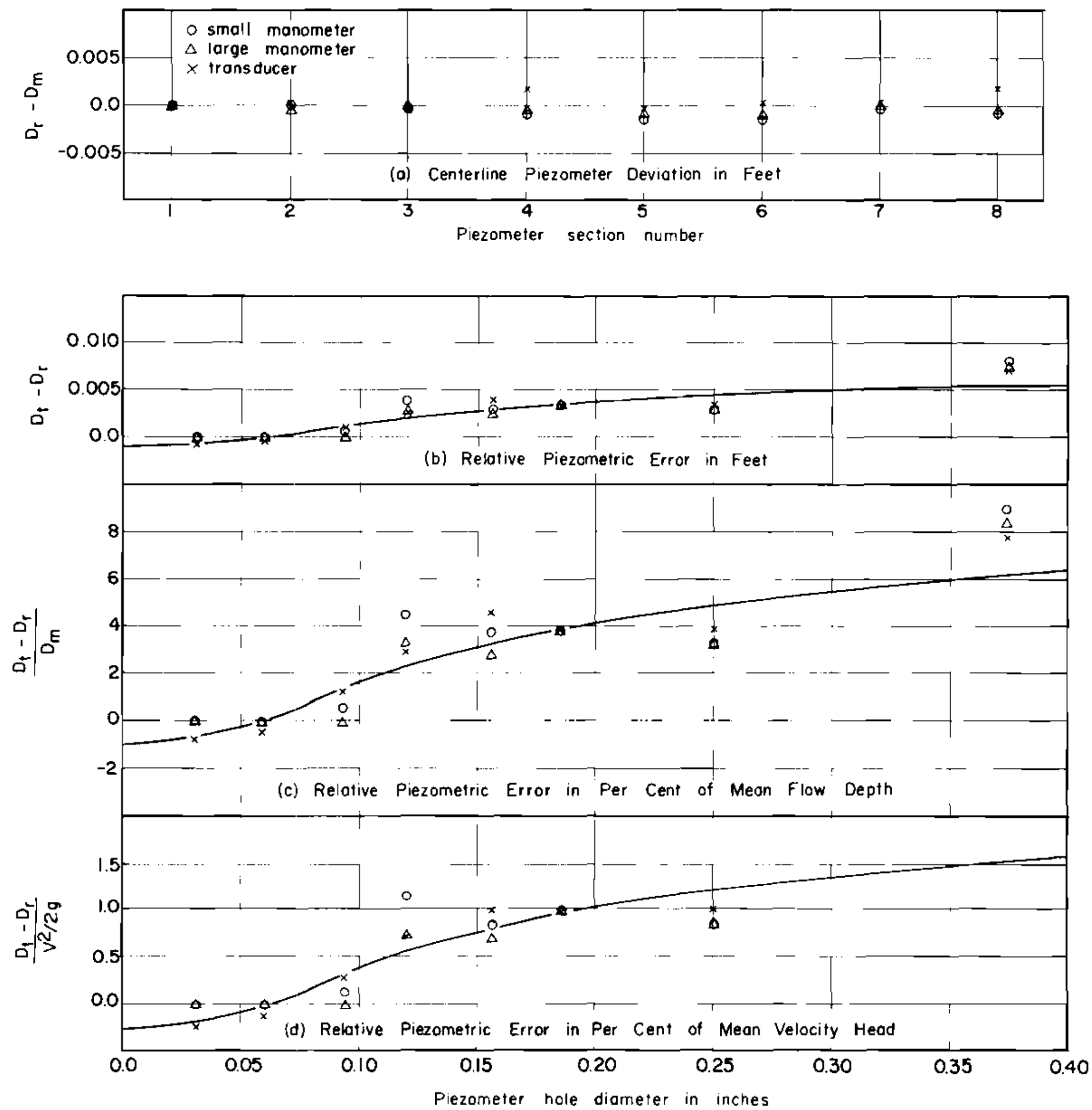


Figure 10. Summary of Data, Test 1.

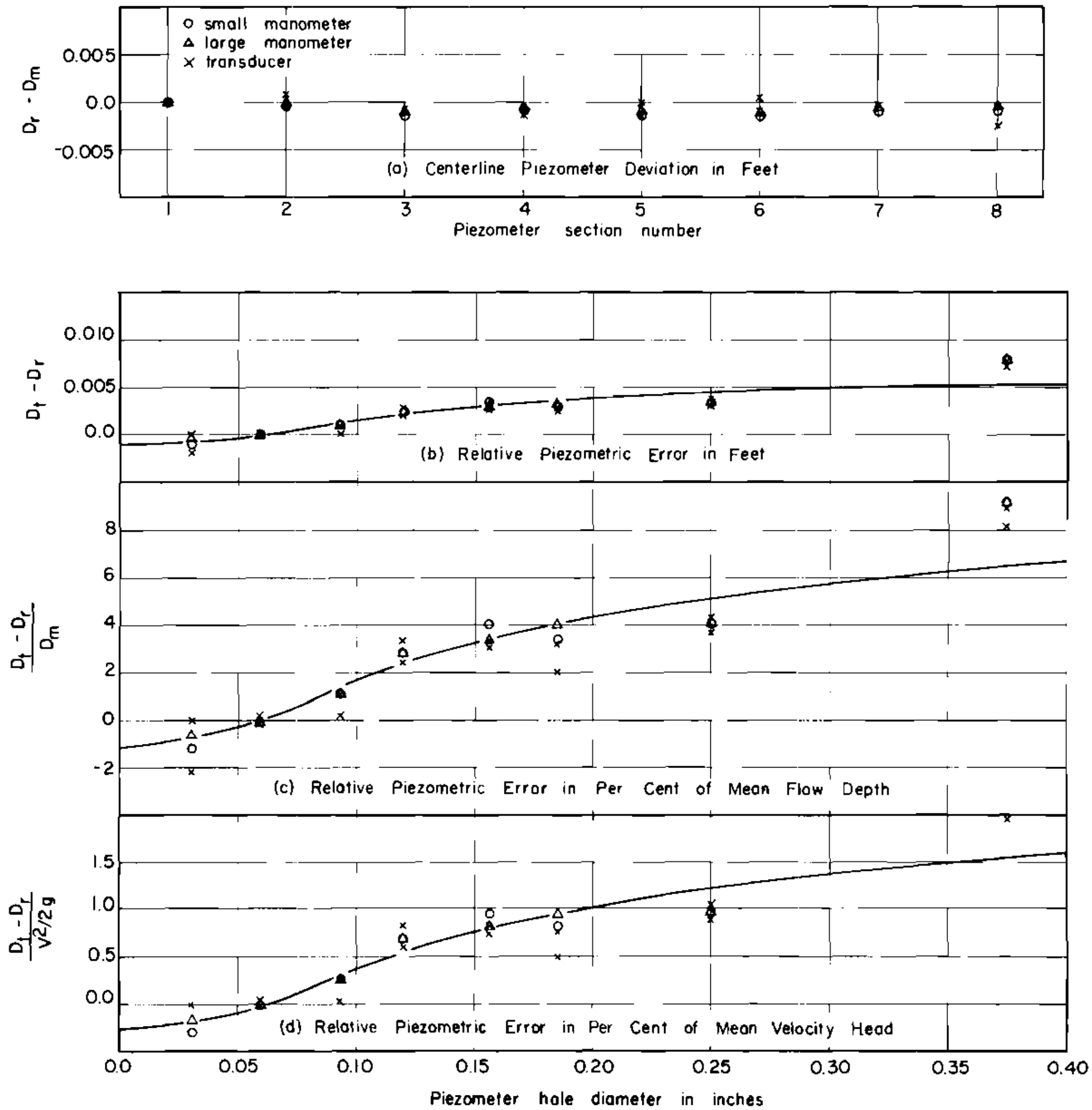


Figure 11. Summary of Data, Test 2.

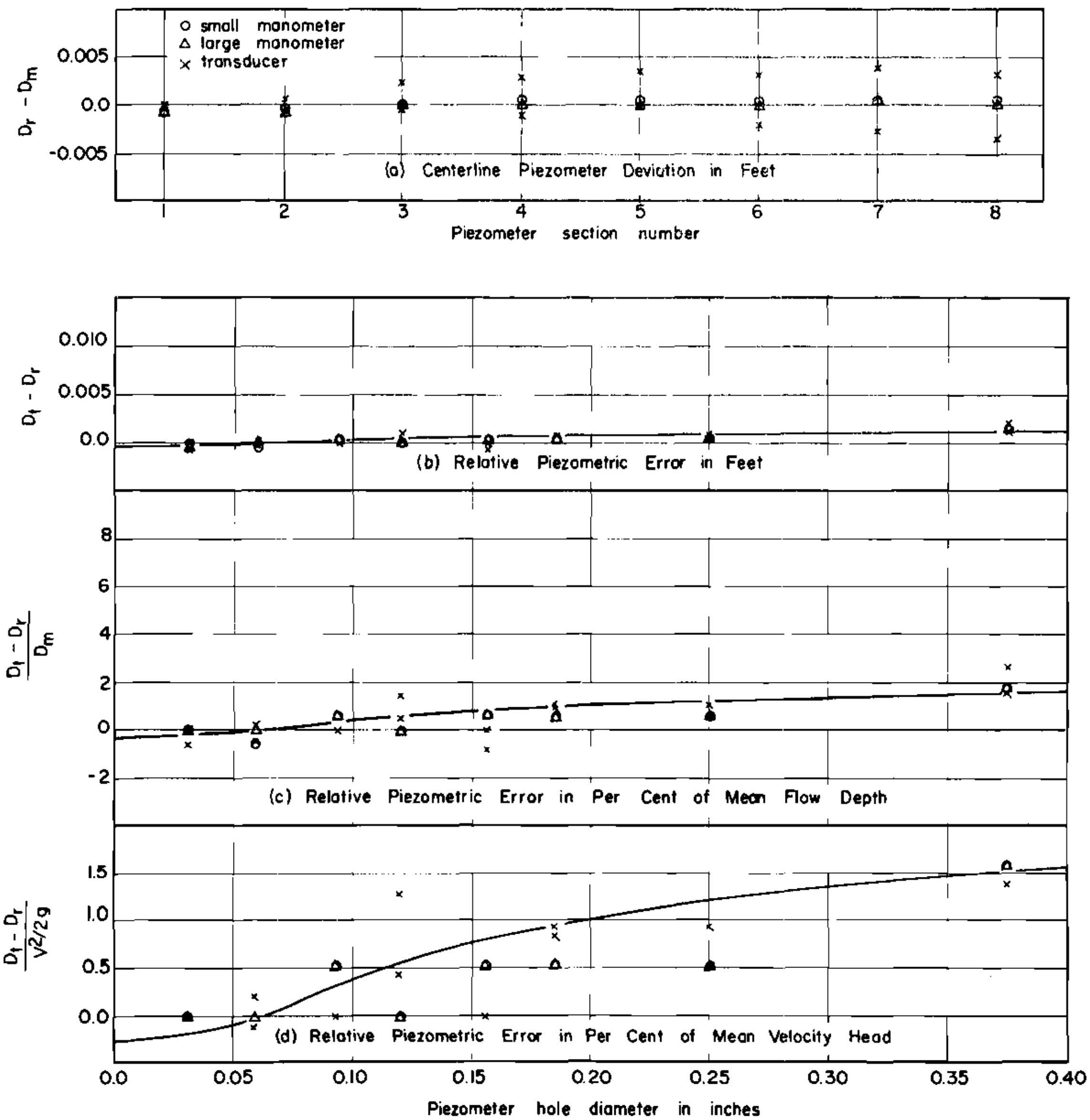


Figure 12. Summary of Data, Test 3.

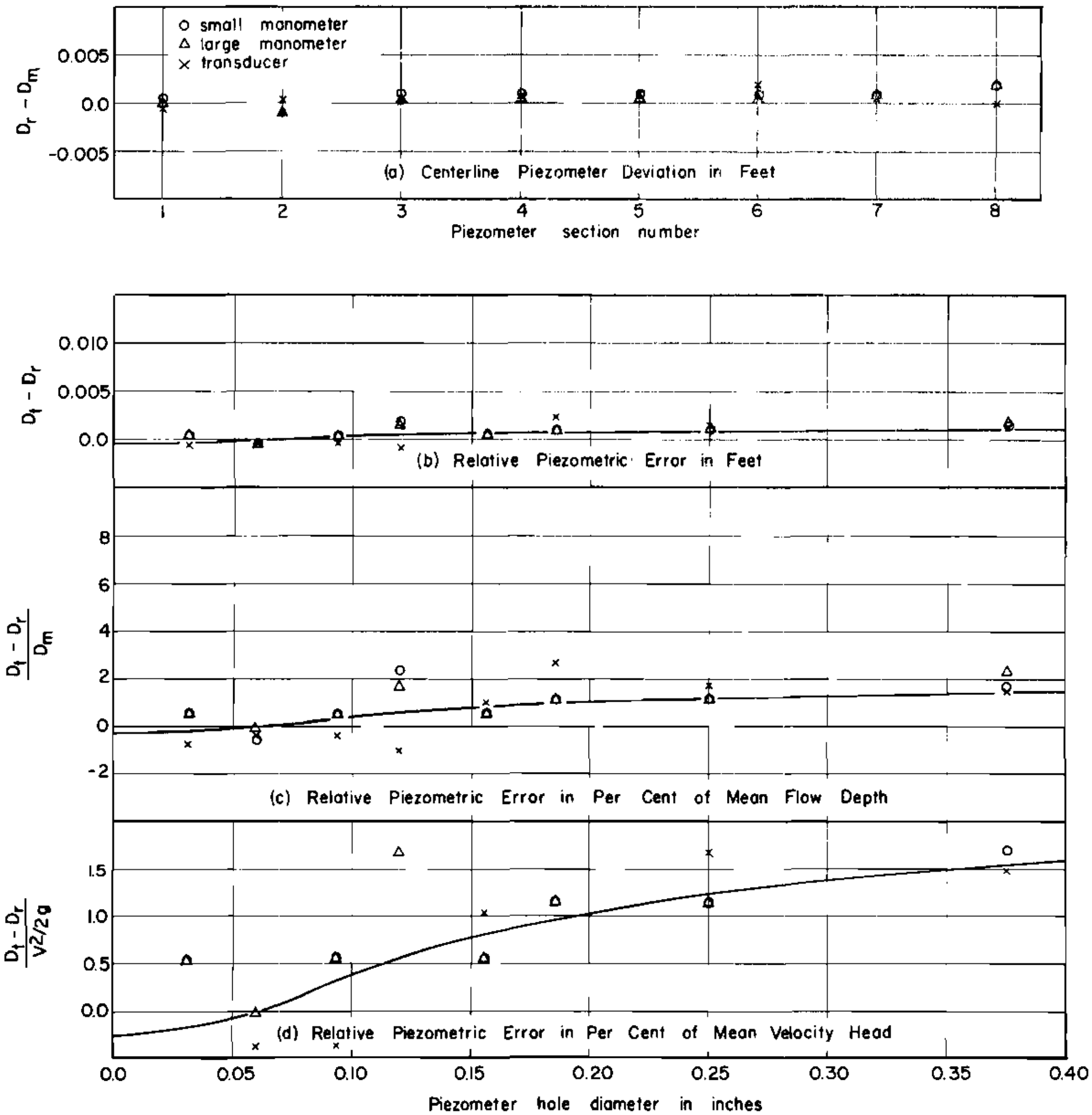


Figure 13. Summary of Data, Test 4.

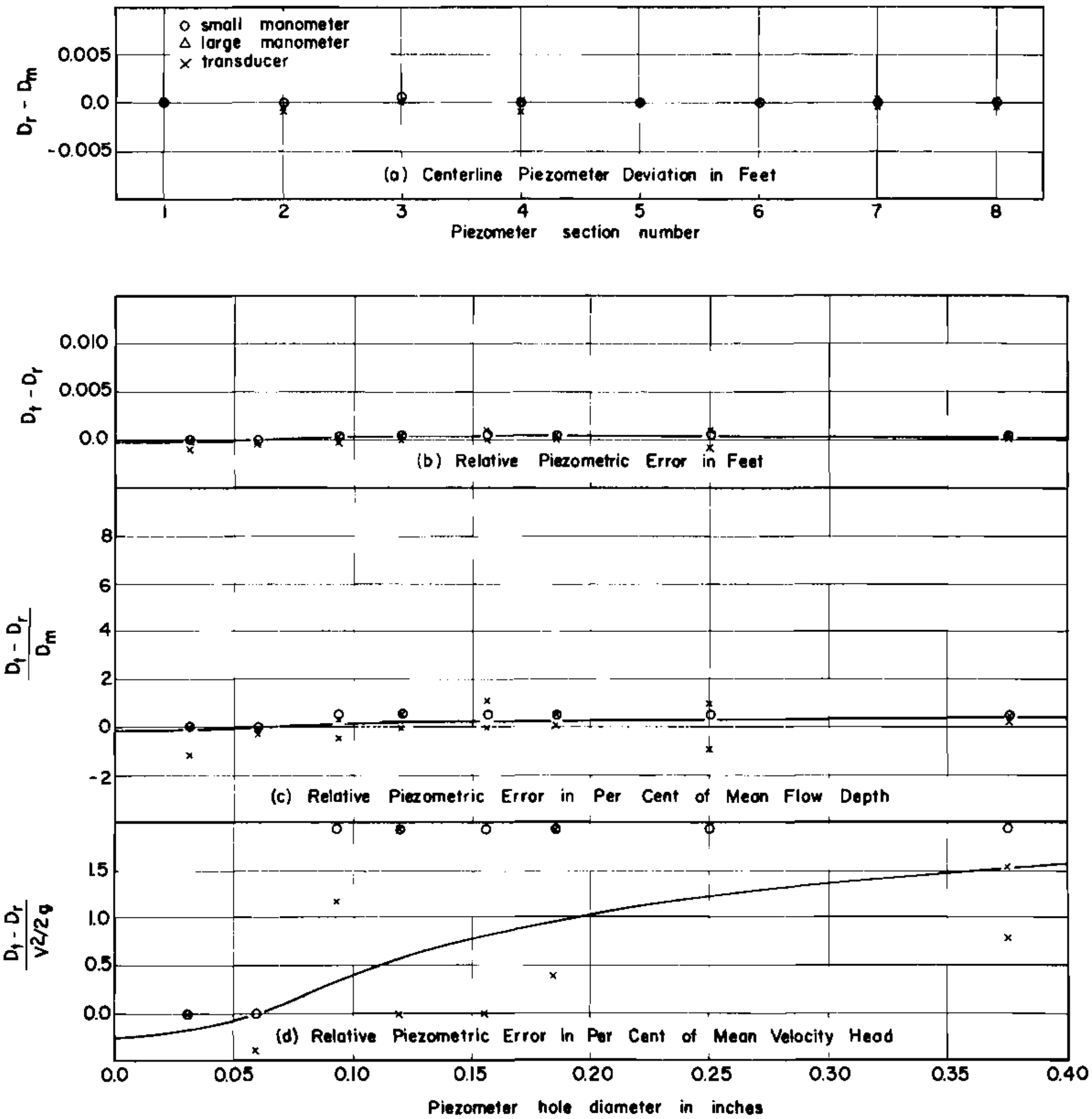


Figure 14. Summary of Data, Test 5.

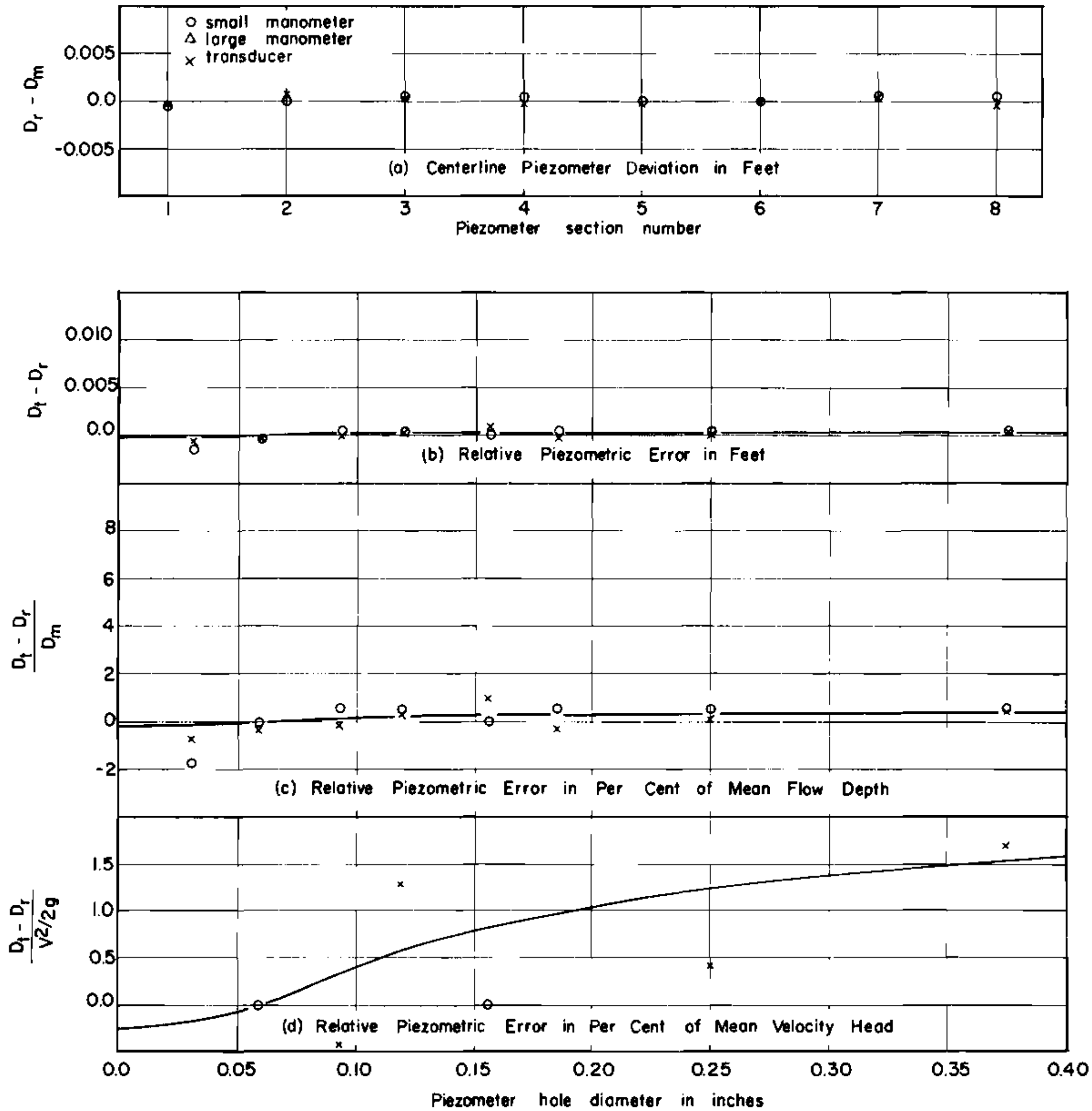


Figure 15. Summary of Data, Test 6.

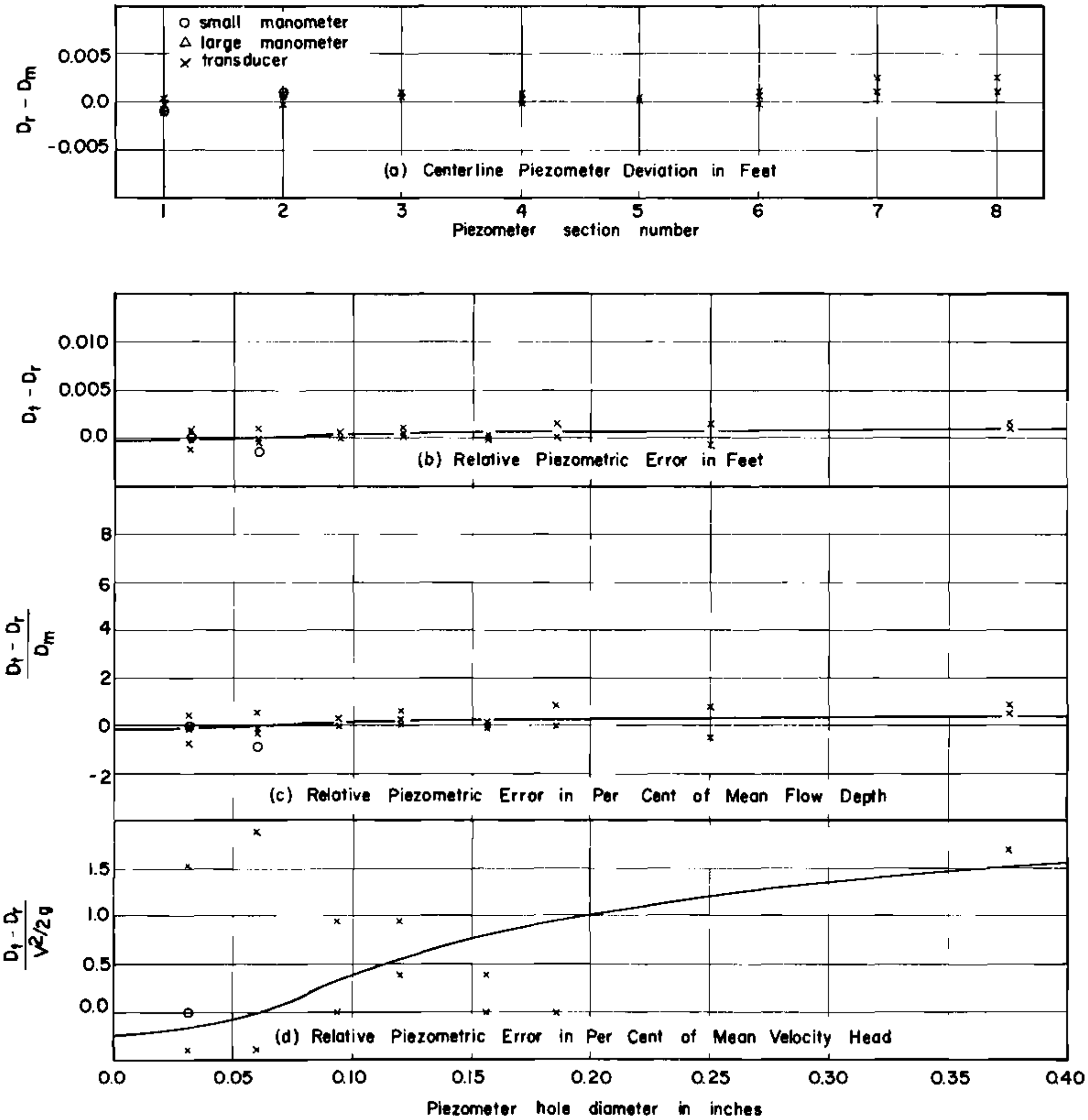


Figure 16. Summary of Data, Test 7.

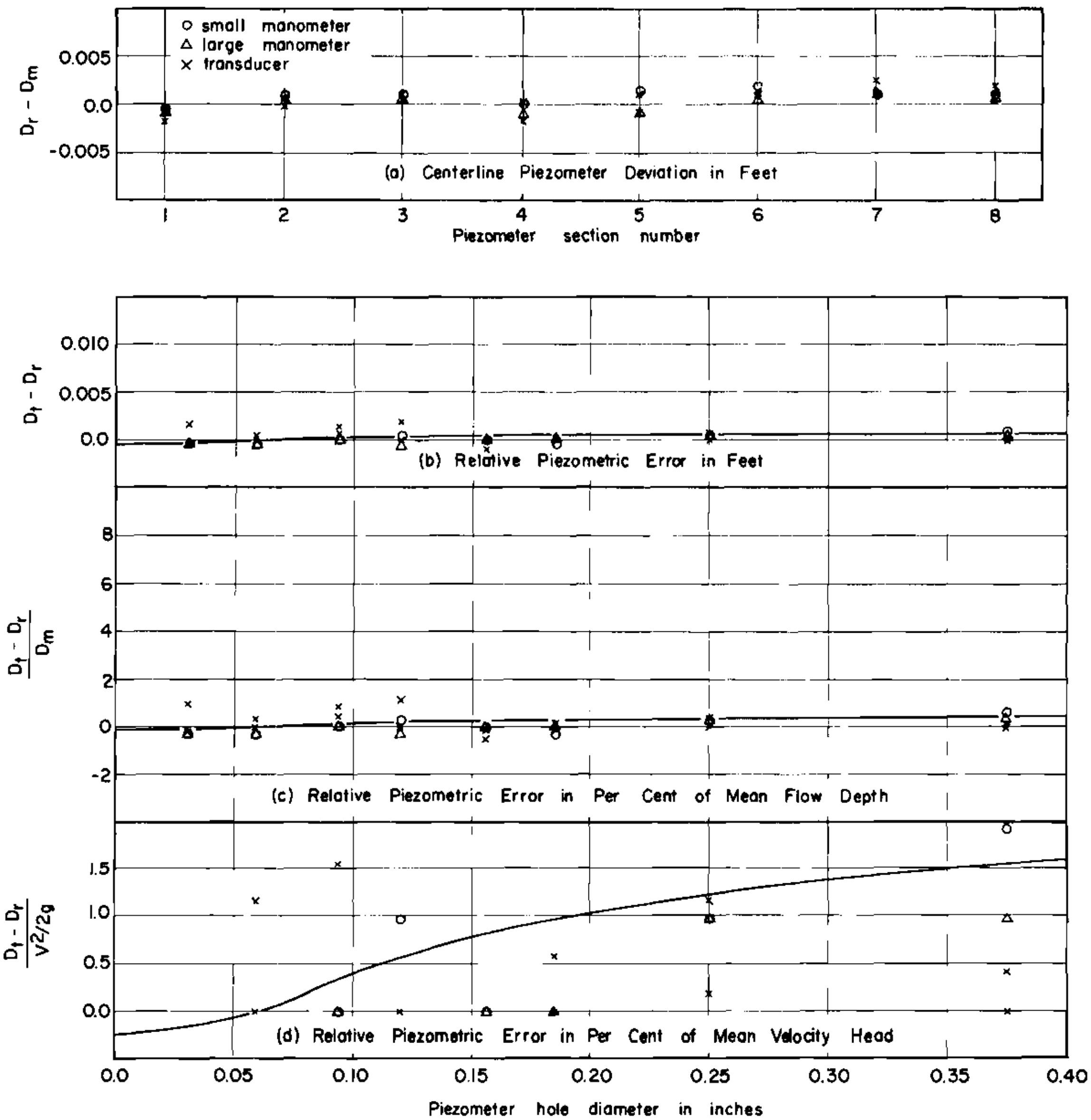


Figure 17. Summary of Data, Test 8.

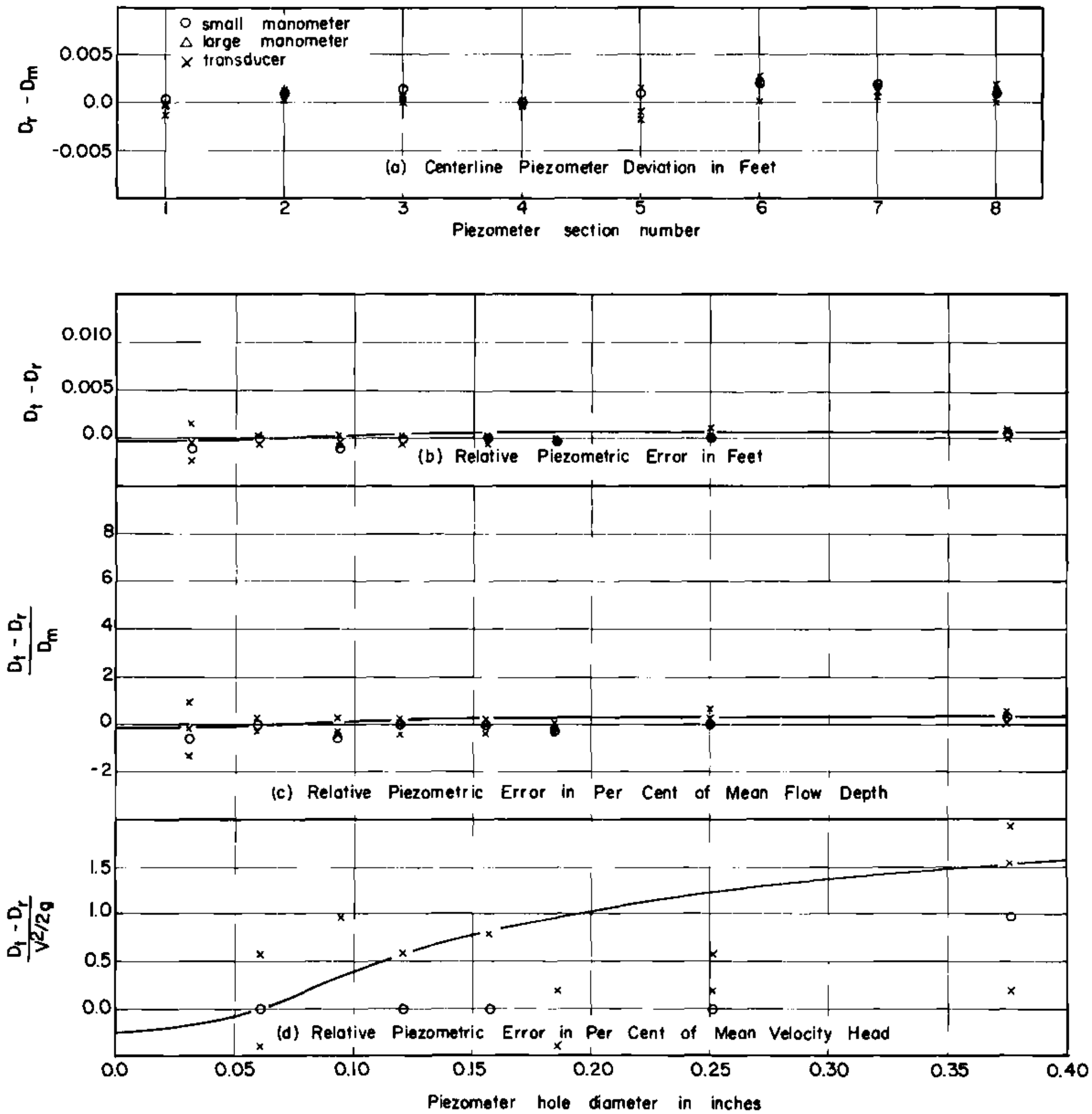


Figure 18. Summary of Data, Test 9.

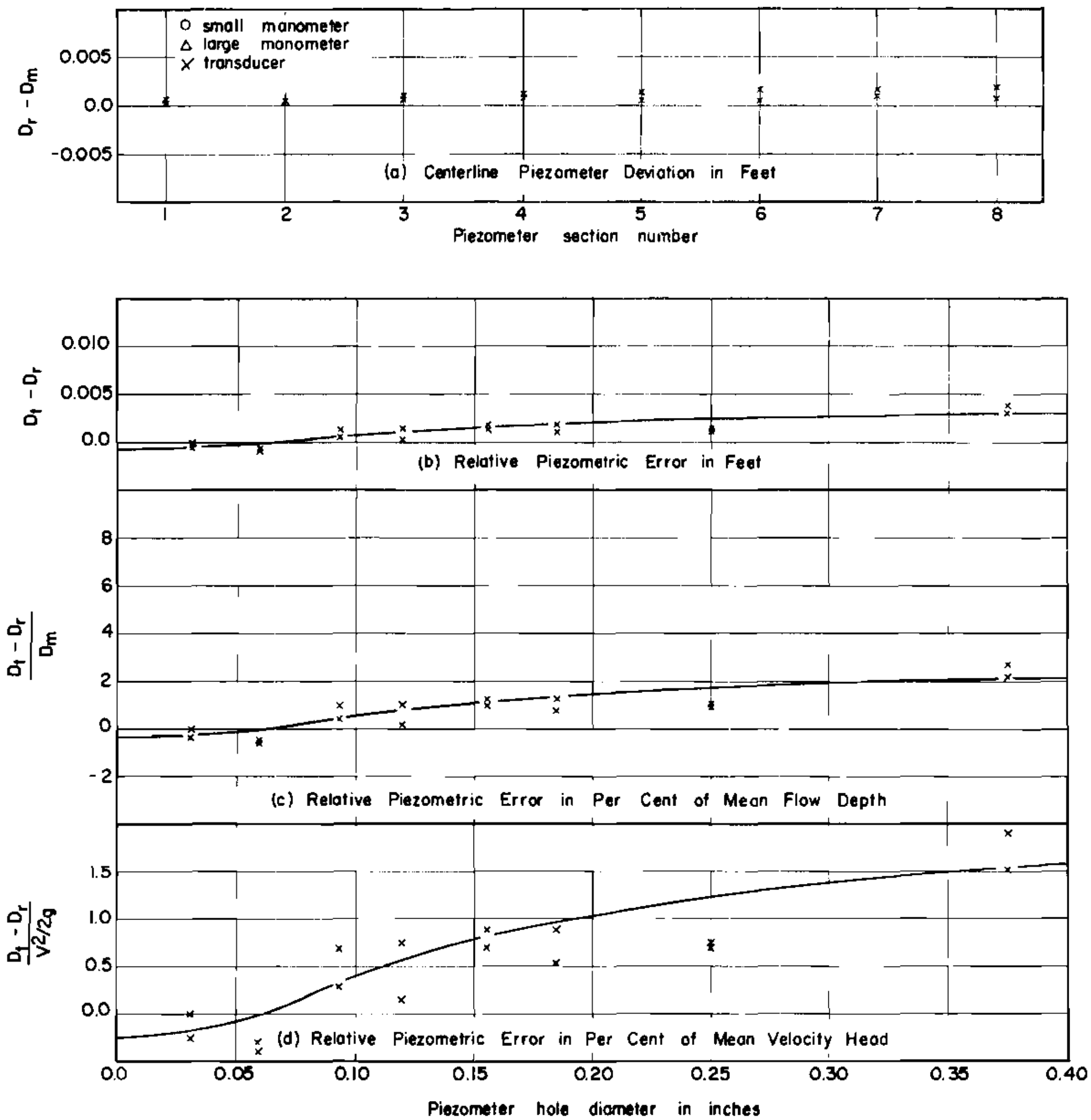


Figure 19. Summary of Data, Test 10.

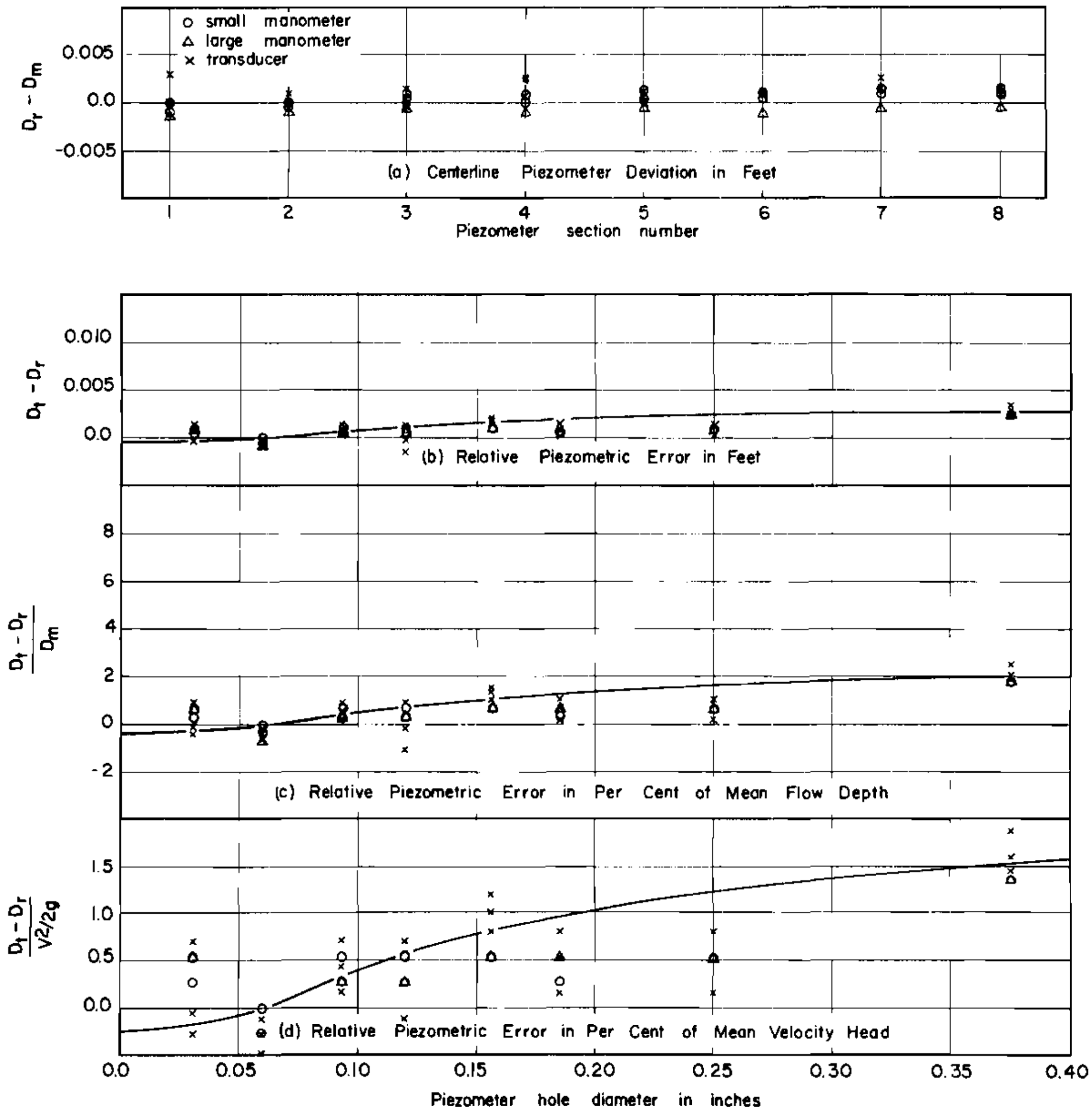


Figure 20. Summary of Data, Test 11.

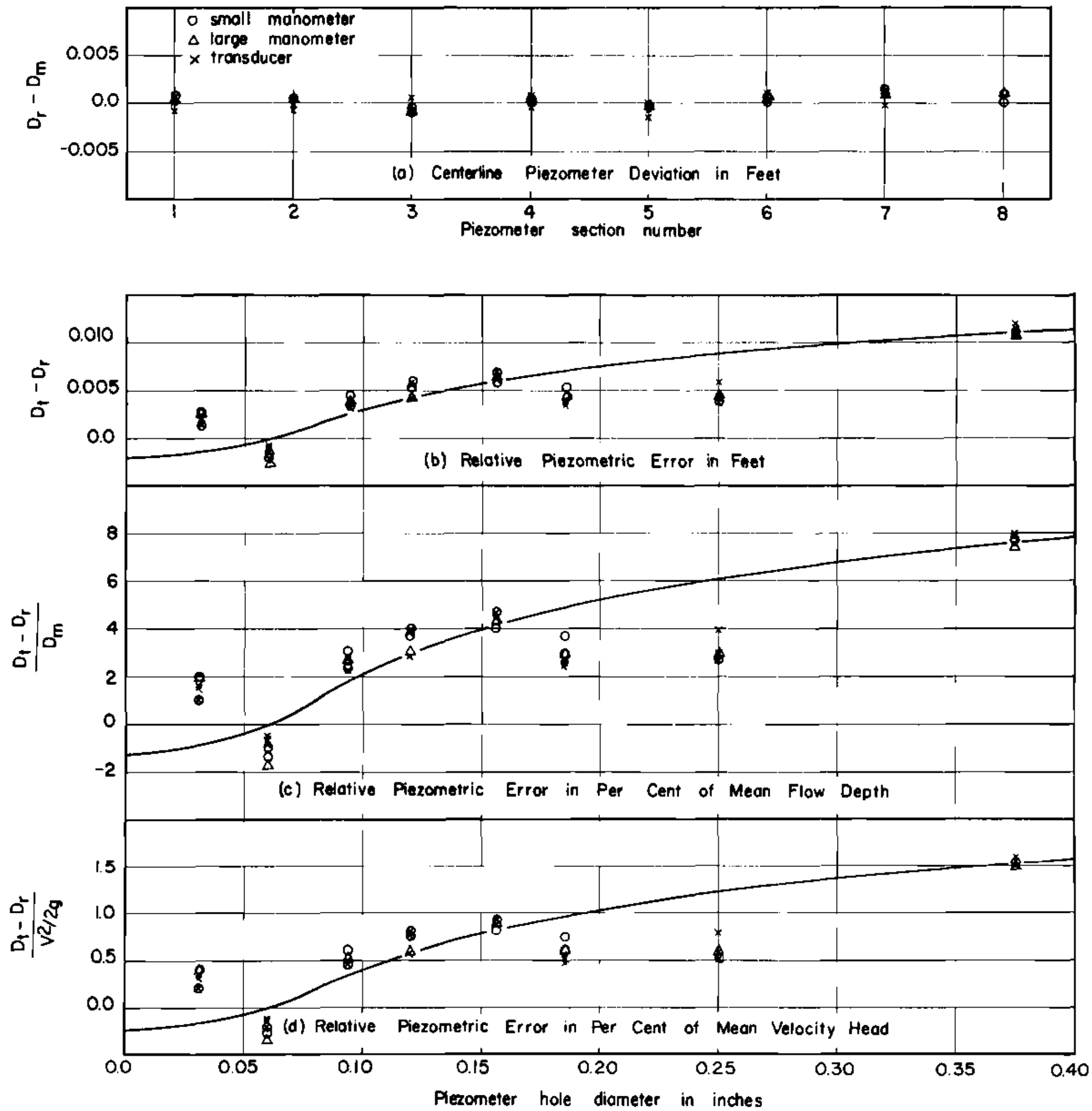


Figure 21. Summary of Data, Test 12.

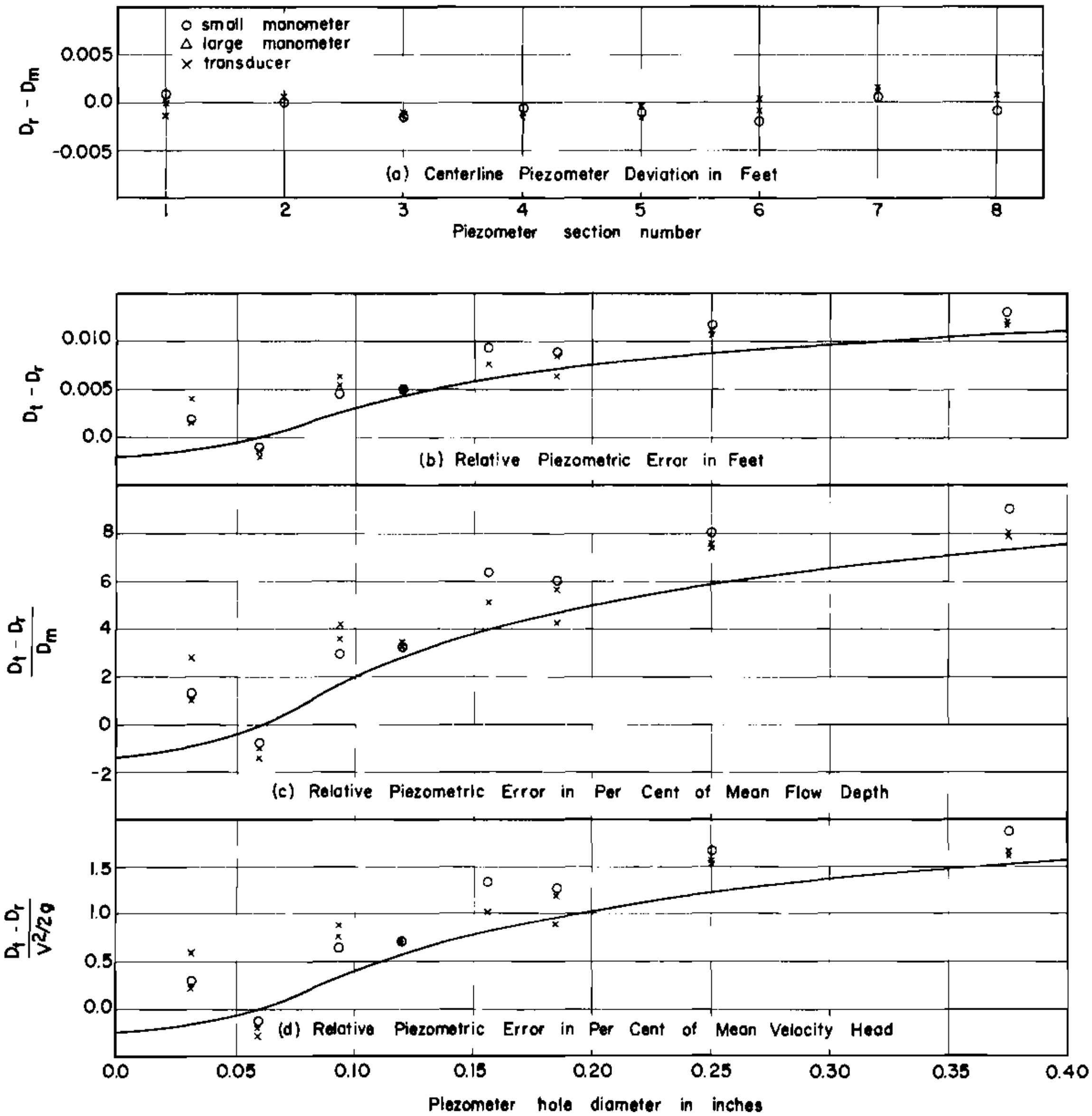


Figure 22. Summary of Data, Test 13.

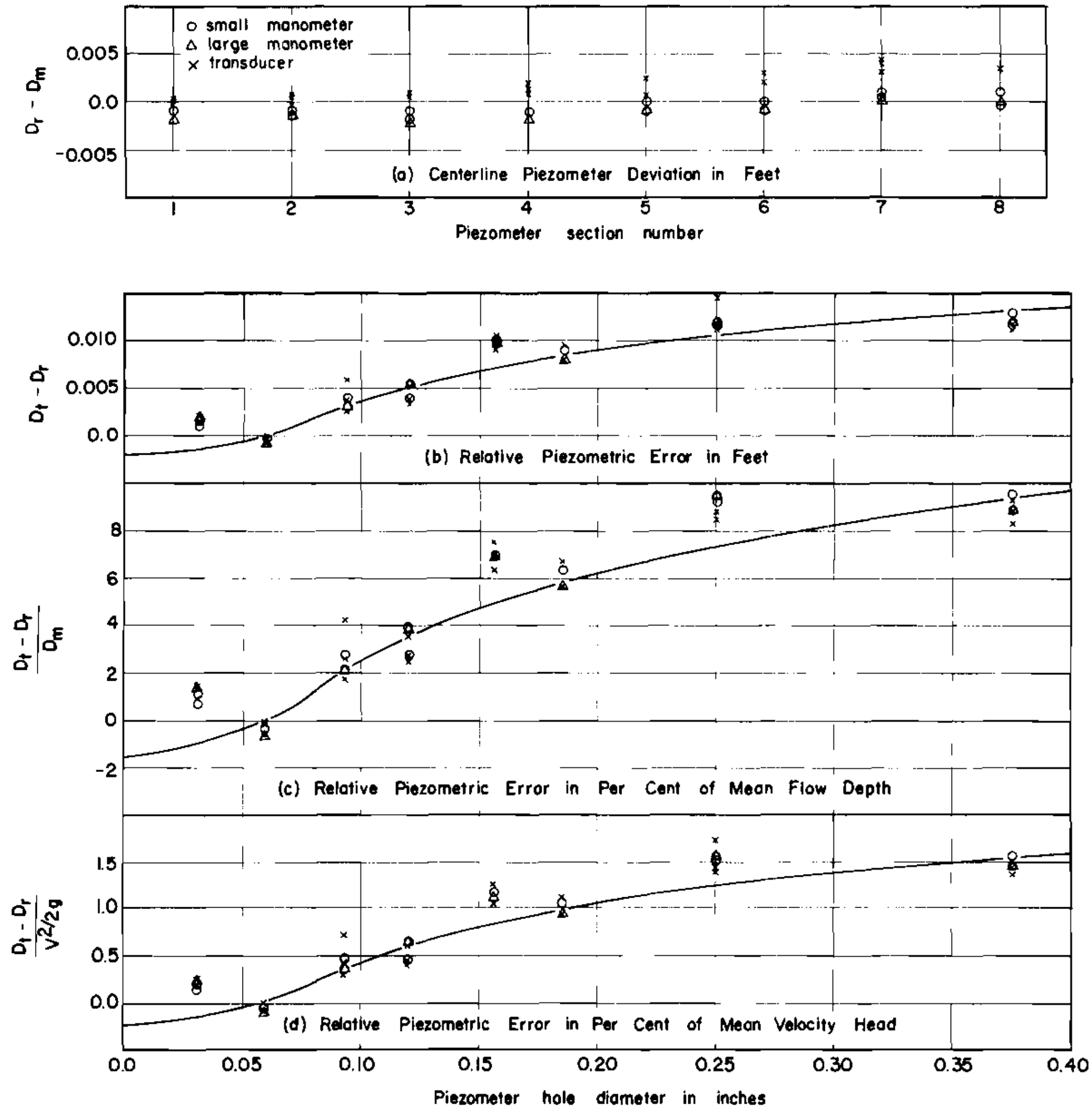


Figure 23. Summary of Data, Test 14.

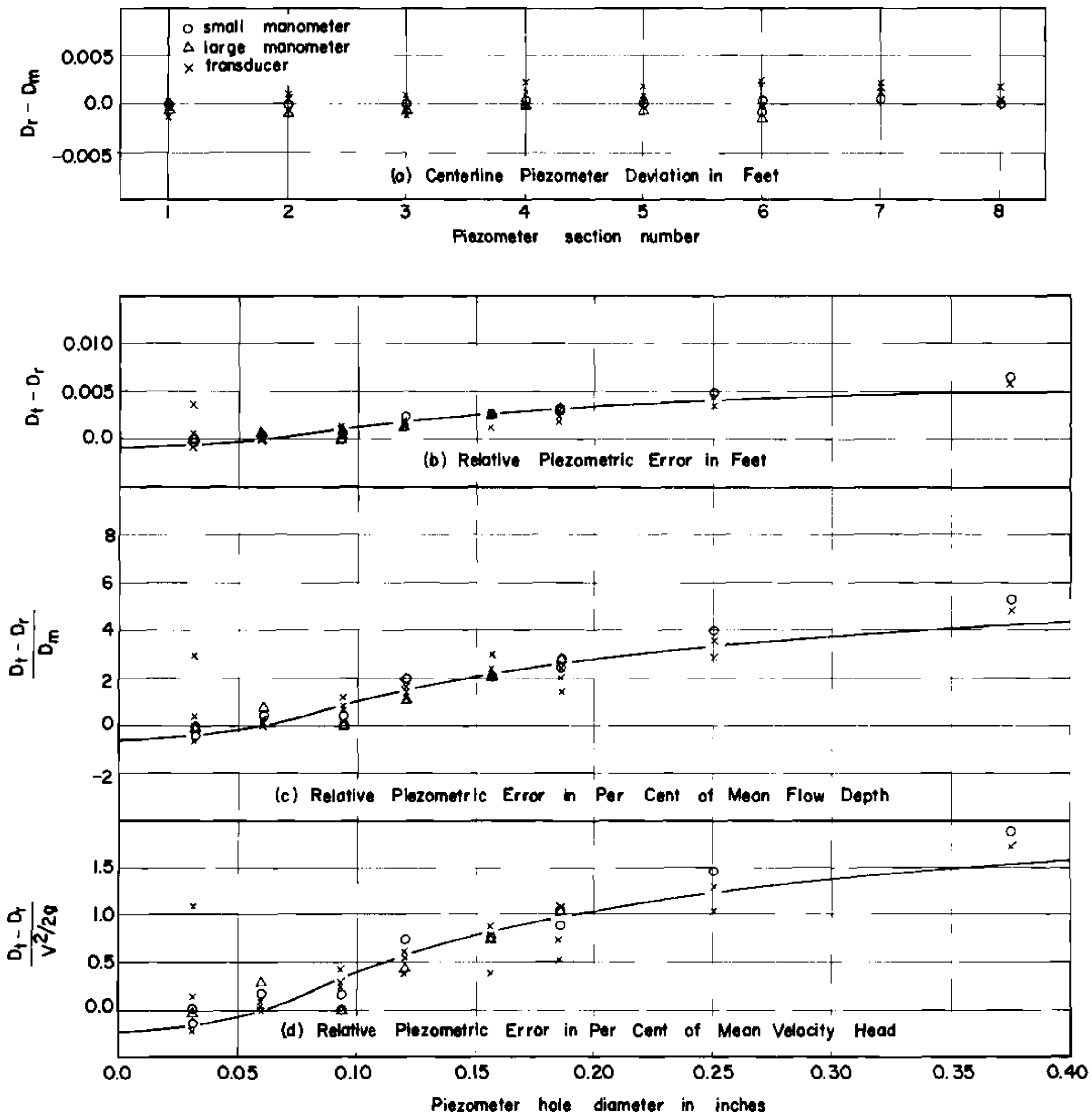


Figure 24. Summary of Data, Test 15.

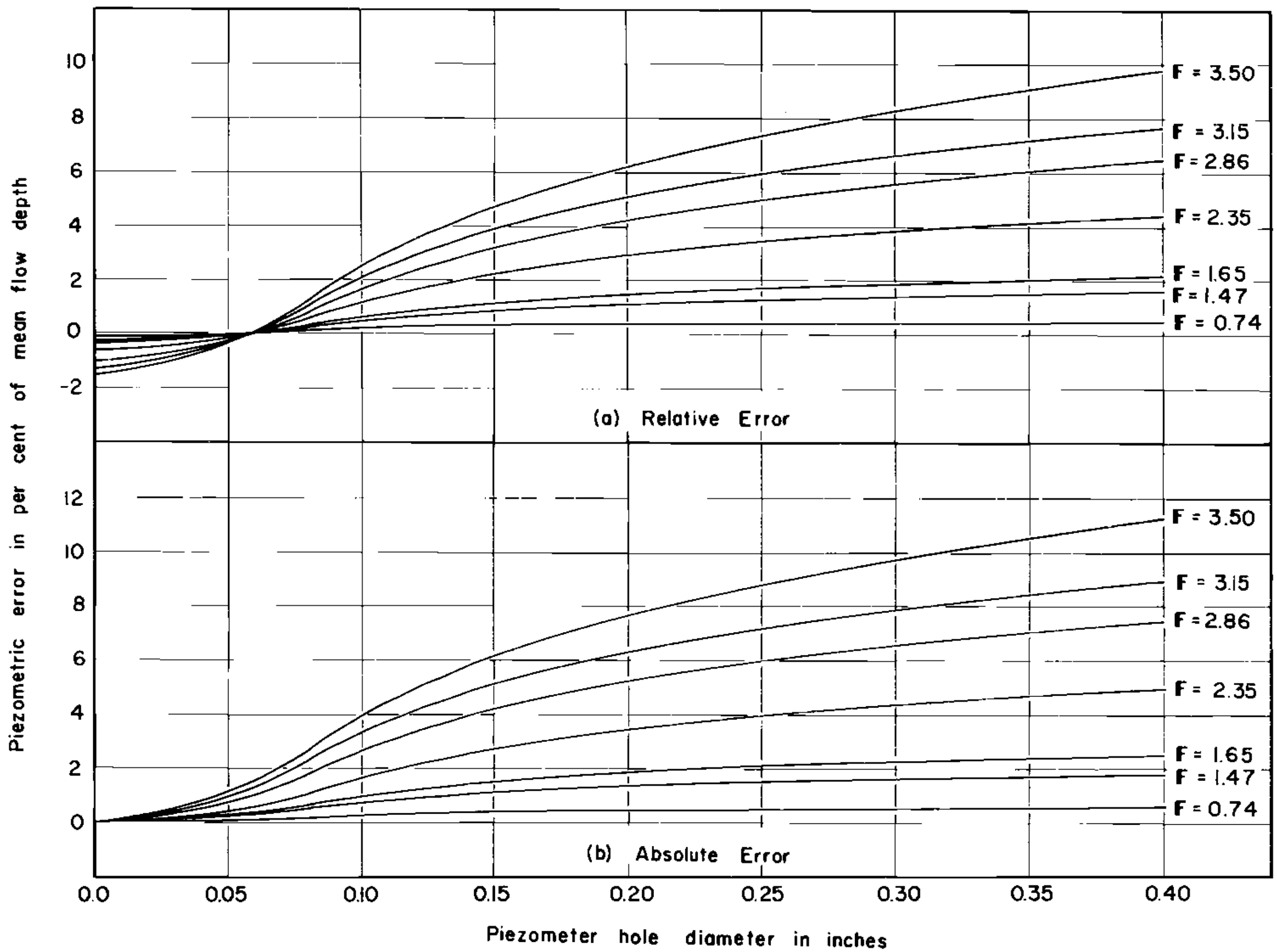


Figure 25. Summary of Curves, Part (c), Figures 10-24.

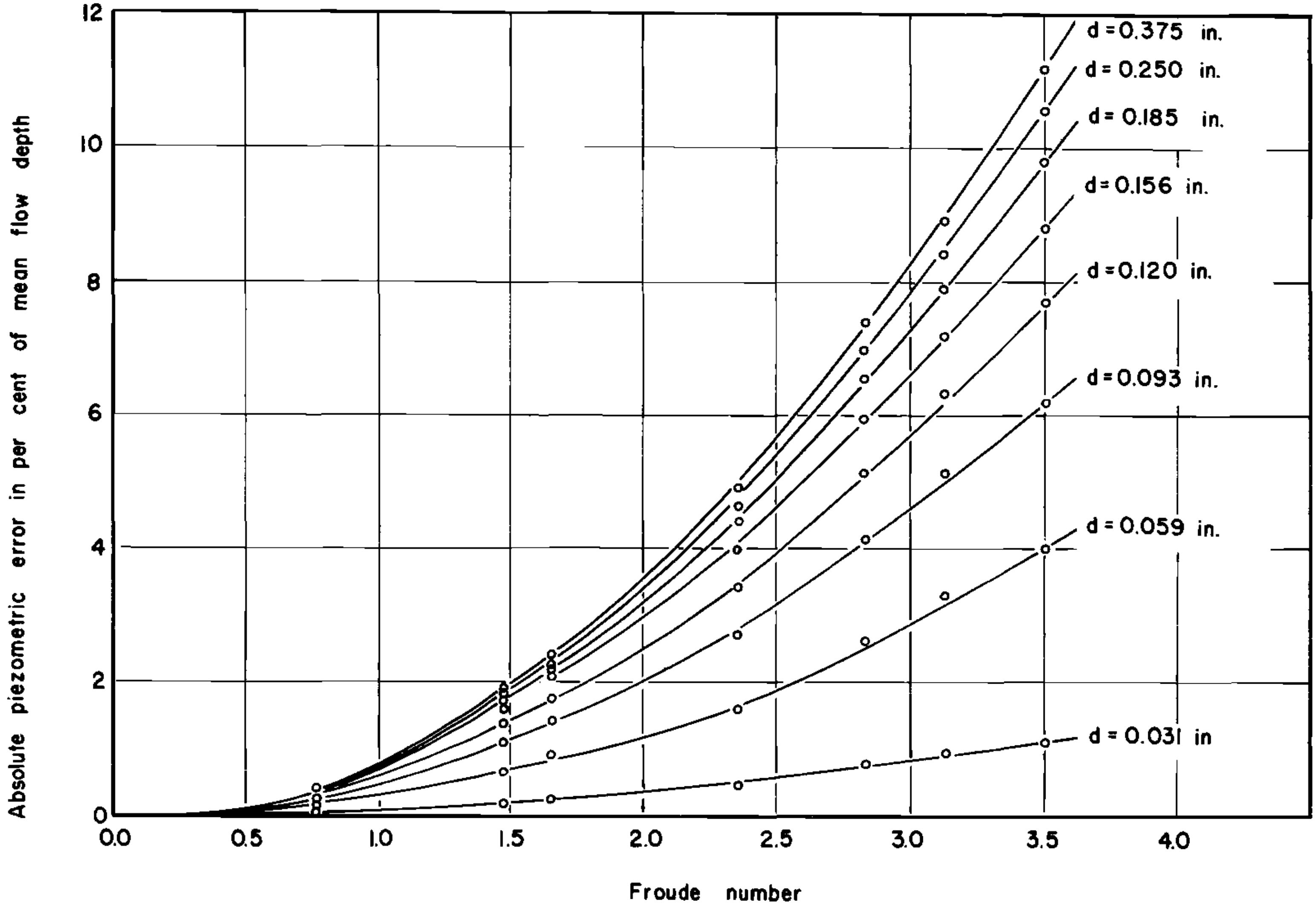


Figure 26. Summary of Curves, Cross-plot of Figure 25 (b).

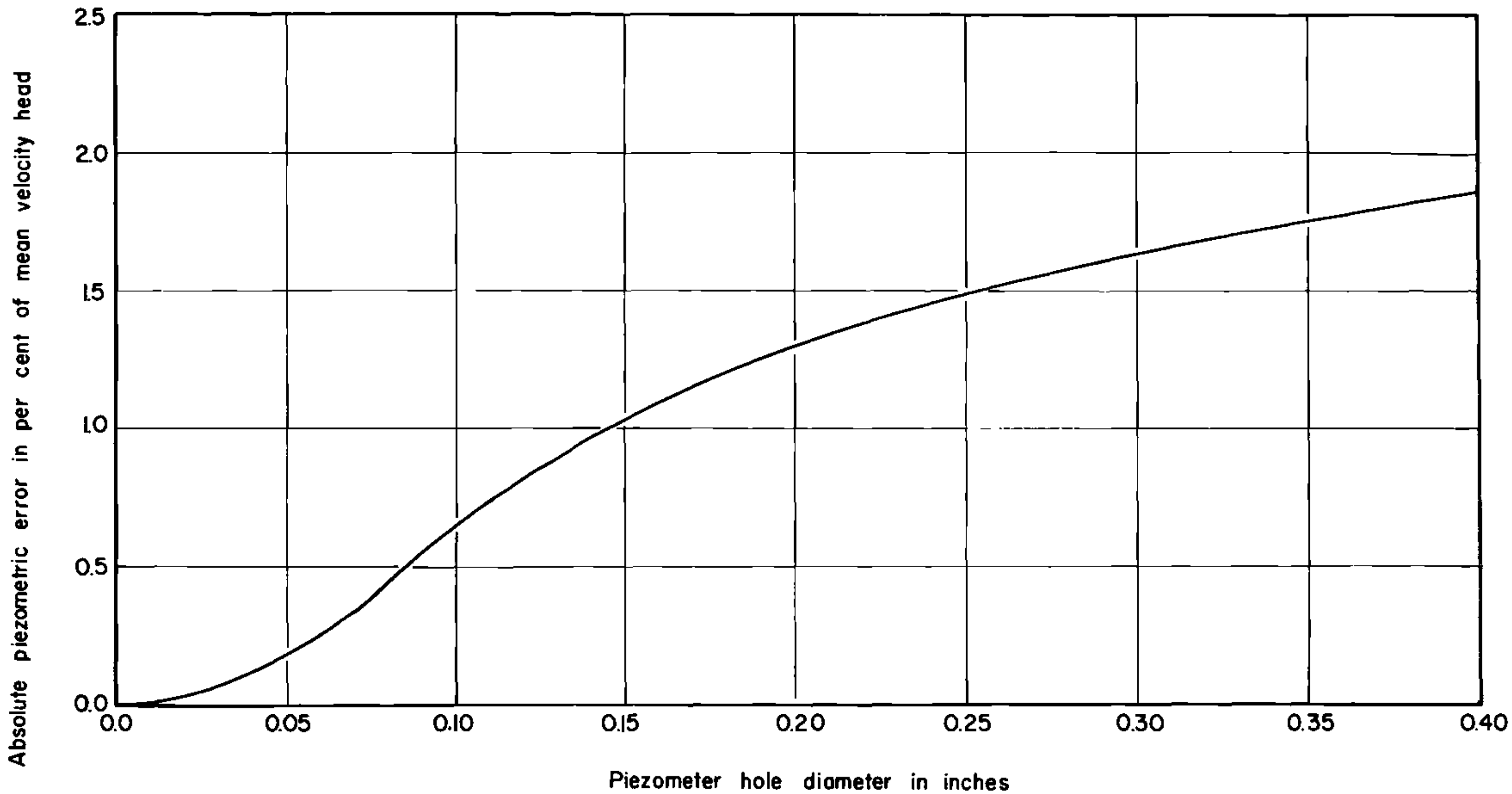


Figure 27. Summary of Curves, Part (d), Figures 10-24.

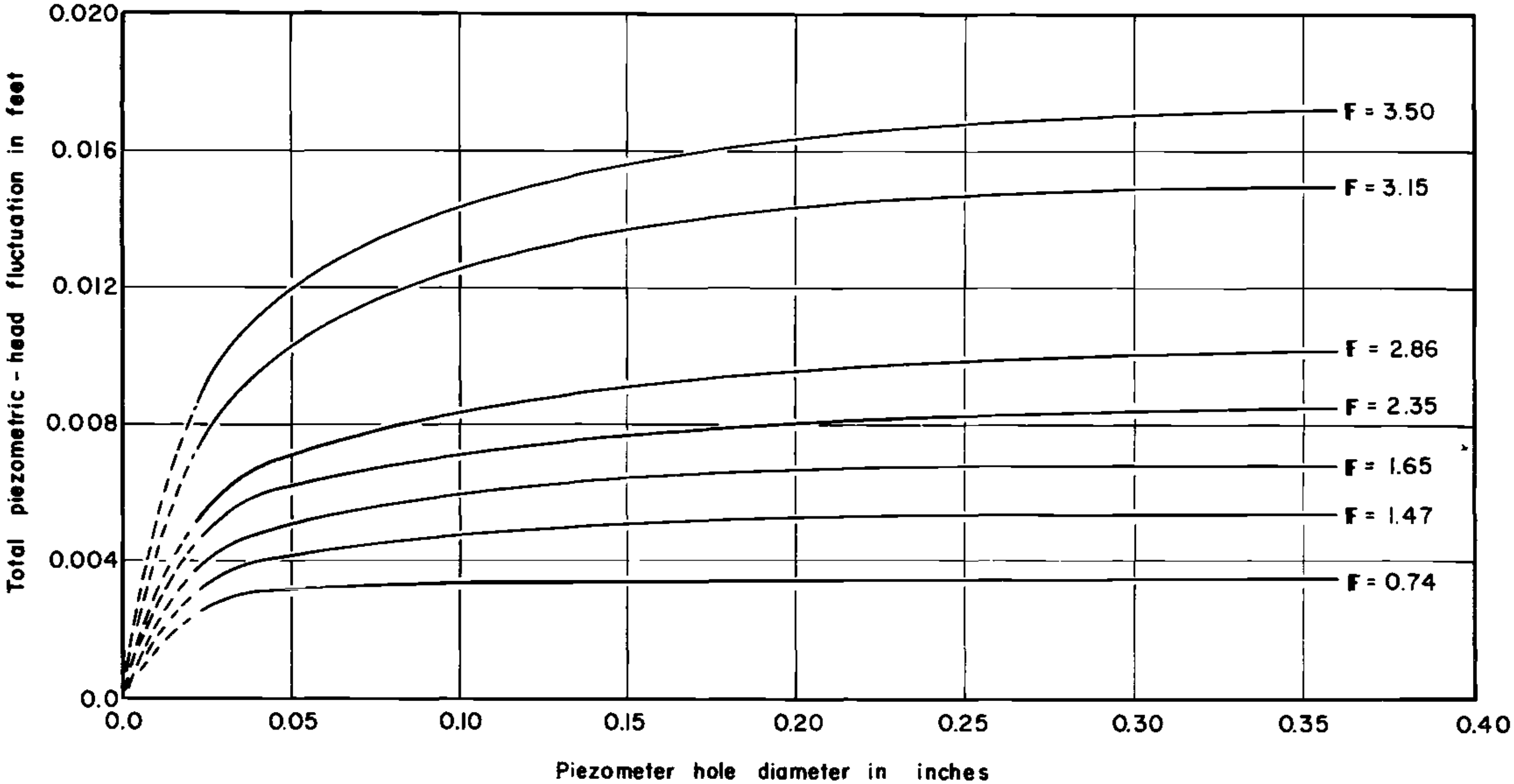


Figure 28. Piezometric-head Fluctuations Recorded by Transducer, Tests 1-15.

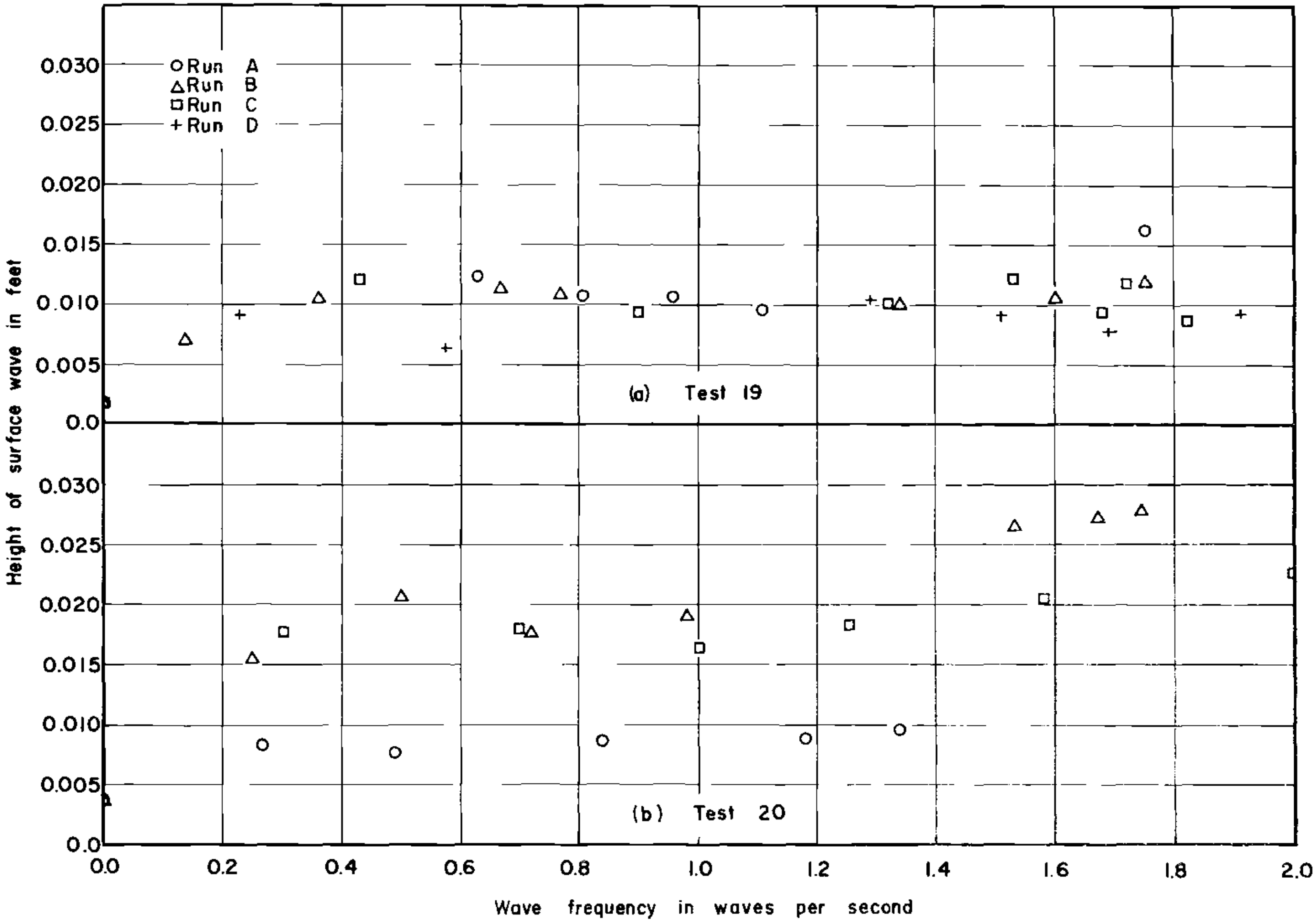


Figure 29. Height of Surface Waves as a Function of the Wave Frequency.

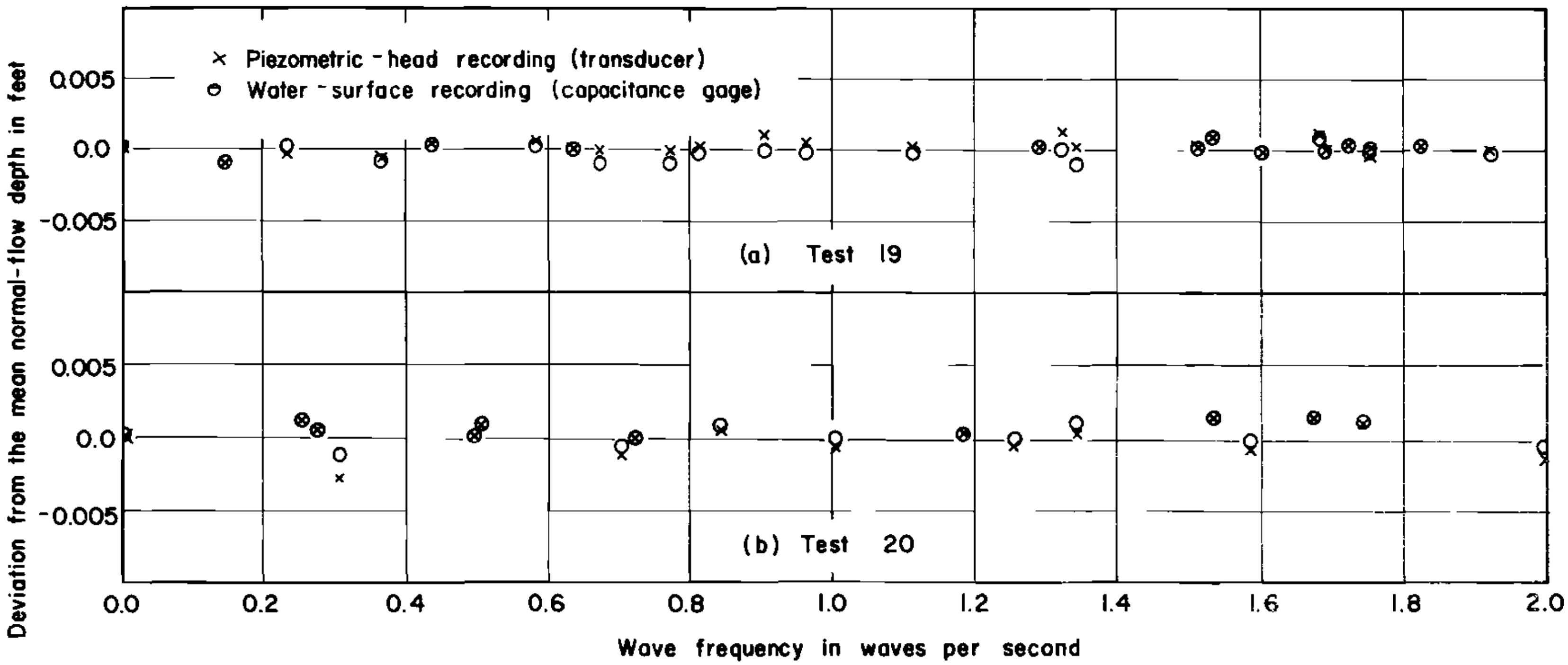


Figure 30. Comparison of Piezometric-head and Water-surface Recordings.